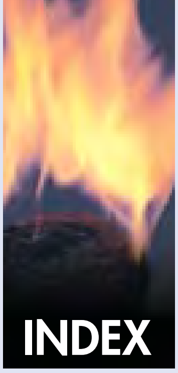
Clean Coal Technologies in Japan

Technological Innovation in the Coal Industry

NEDO



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Technological Innovation in the Coal Industry

(1) Technologies for Coal Resources Development

(2) Coal-fired Power Generation Technologies

A. Combustion Technologies

B. Gasification Technologies

(3) Iron Making and General Industry Technologies

A. Iron Making Technologies

B. General Industry Technologies

(4) Multi-purpose Coal Utilization Technologies

A. Liquefaction Technologies

B. Pyrolysis Technologies

C. Powdering, Fluidization, and Co-utilization Technologies

D. De-ashing and Reforming Technologies

(5) Environmental Protection Technologies

A. CO_2 Recovery Technologies

B. Flue Gas Treatment and Gas Cleaning Technologies

C. Technologies to Effectively Use Coal Ash

(6) Basic Technologies for Advanced Coal Utilization

(7) Co-production Systems

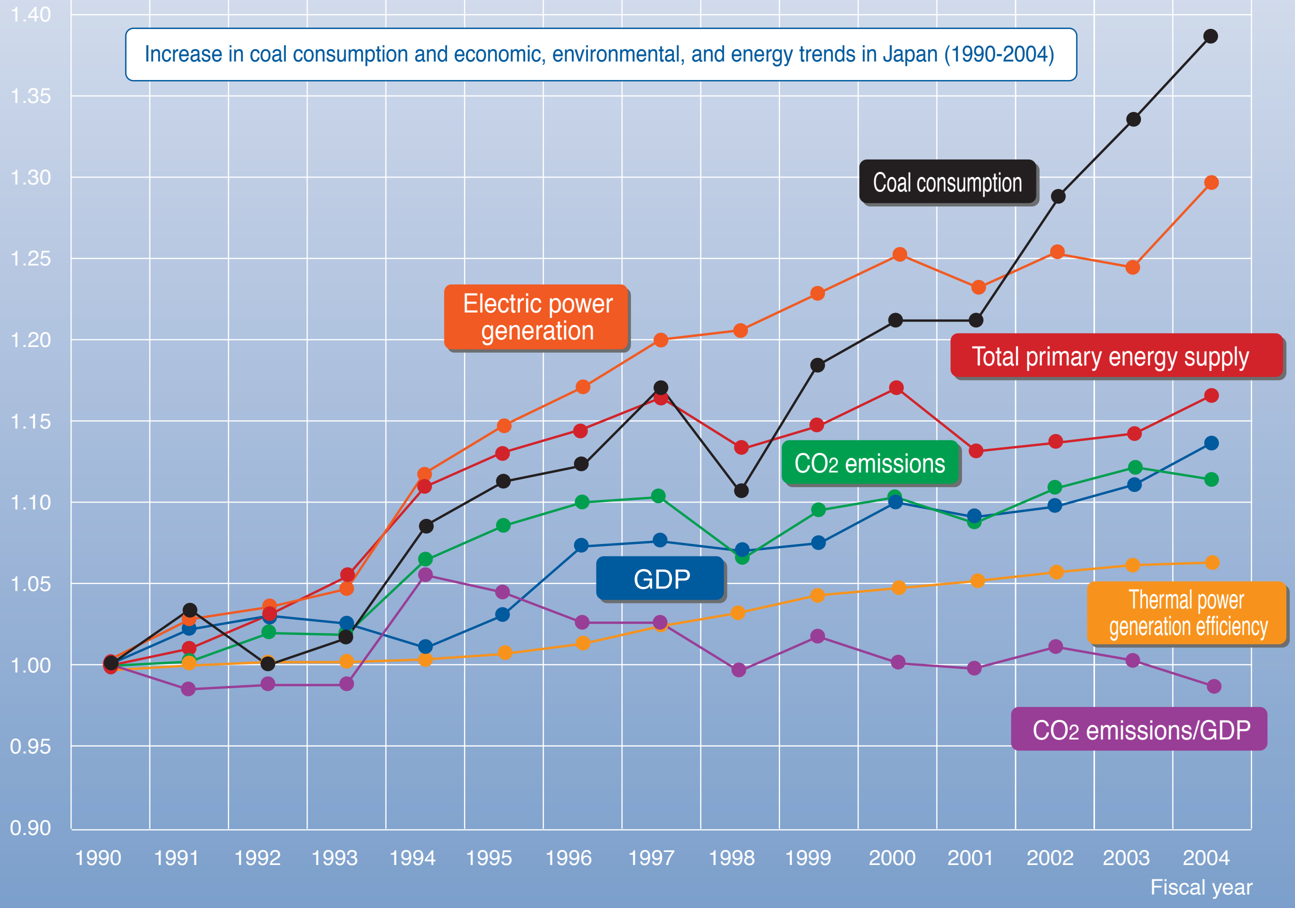
Preface

The New Energy and Industrial Technology Development Organization (NEDO) and the Japan Coal Energy Center (JCOAL) have jointly prepared this guide as a review of the history of "Clean Coal Technology (CCT)" in Japan, to systematically describe the present state of CCT insofar as possible, and to provide useful material for novel technological innovation.

NEDO and JCOAL hope this brochure will be helpful in elucidating why Japan's CCT is an attractive technology in the ever-increasing complexity of coal utilization owing to global warming and other environmental issues. NEDO and JCOAL also hope this brochure will encourage rapid progress in CCT development and the foundation of innovative clean coal utilization systems.

As described herein, CCT development in Japan has reached the world's highest level of technological superiority, making the technology highly attractive to Asian countries that depend on coal as an energy source. In Japan, coal consumption has rapidly increased since 1998, with gross thermal power generation efficiency increasing from approximately 38% to 41% over the past dozen or so years. In addition, emissions of CO_2, SOx and NOx per generated power unit from thermal power plants are far below the level of other industrialized countries. In this regard, CCT is expected to become standardized worldwide, satisfying both economic and environmental requirements by reducing CO_2 emissions and maintaining GDP growth.

Technological innovation has no boundaries; significant progress can be attained sustainably and progressively. Patient, consistent efforts to build on technological developments can support a continually evolving society. NEDO and JCOAL are confident this publication will contribute to CCT development and we look forward to the emergence of dramatic technological innovations in the coal industry.

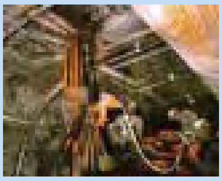


CCT Classifications in the Coal Product Cycle


Coal exploration


Coal mine


Coal tanker


Cave-in prediction


Coal preparation plant


Coal train


EAGLE


DME


SCOPE21

Gasification

Liquefaction

Slurry preparation

Pulverizing/Briquetting

Carbonization

DME/GTL

Exploration, mining, safety and preparation

Crushing, transportation and storage

Processing, reforming and converting

Technologies for Coal Resources Development
- **1A1** Coal Resource Exploration Technology
- **1A2** Coal Production Technology
- **1A3** Mine Safety Technology
- **1A4** Environment-friendly Resource Development Technology

Multi-purpose Coal Utilization Technologies
- **Coal Gasification and Hydrogenation Technologieies**
  - **2B1** Hydrogen-from-Coal Process (HYCOL)
  - **2B3** Multi-purpose Coal Gasification Technology Development (EAGLE)
  - **5A1** Hydrogen Production by Reaction Integrated Novel Gasification Process (HyPr-RING)
- **Liquefaction Technologies**
  - **4A1** Coal Liquefaction Technology Development in Japan
  - **4A2** Bituminous Coal Liquefaction Technology (NEDOL)
  - **4A3** Brown Coal Liquefaction Technology (BCL)
  - **4A4** Dimethyl Ether Production Technology (DME)
- **Pyrolysis Technologies**
  - **4B1** Multi-purpose Coal Conversion Technology (CPX)
  - **4B2** Efficient Co-production with Coal Flash Partial Hydropyrolysis Technology (ECOPRO)
- **Powdering, Fluidization and Co-utilization Technologies**
  - **4C1** Coal Cartridge System (CCS)
  - **4C2** Coal Water Mixture Production Technology (CWM)
  - **4C3** Briquette Production Technology
  - **4C4** Coal and Woody Biomass Co-firing Technology
- **De-ashing and Reforming Technologies**
  - **4D1** Hyper-coal-based High-efficiency Combustion Technology (Hyper-coal)
  - **4D2** Low-rank Coal Upgrading Technology (UBC Process)
- **Basic Technologies for Advanced Coal Utilization**
  - **6A1** Modeling and Simulation Technologies for Coal Gasification

Physical properties of coal

	Anthracite	Bituminous coal	Brown coal
Specific gravity	1.5-1.8	1.2-1.7	0.8-1.5
Apparent specific gravity	-	0.75-0.80	0.55-0.75
Specific heat	0.22-0.24	0.24-0.26	0.26-0.28
Thermal conductivity (W/m·K)	-	1.26-1.65	-
Ignition point (°C)	400-450	300-400	250-300
Heating value (kcal/kg(dry basis))	8,200-8,500	7,500-8,800	5,500-7,500

Coal classification by degree of carbonization

Classification	Heating value (kcal/kg(dry basis))	Fuel ratio	Caking property
Anthracite	-	4.0 or greater	Non-caking
Bituminous coal	8,400 or greater	1.5 or greater	Strong-caking
		1.5 or less	
	8,100 or greater	1.0 or greater	Caking
		1.0 or less	Weak-caking
Subbituminous coal	7,800 or greater	1.0 or greater	Weak-caking
		1.0 or less	Non-caking
	7,300 or greater	-	Non-caking
Brown coal	6,800 or greater	-	Non-caking
	5,800 or greater		

Coal classification by utilization (expressed as coal)

Source: TEXT report		*Source: Trade Statistics*		
Anthracite		Anthracite		
Coking coal	Coking coal A	Bituminous coal	Strong-caking coal for coke	Ash content of 8% or less
	Coking coal B			Ash content exceeding 8%
	Coking coal C		Other coal for coke	Ash content of 8% or less
	Coking coal D			Ash content exceeding 8%
Steam coal	Steam coal A		Other	Ash content exceeding 8%
	Steam coal B	Other coal		Ash content of 8% or less
	Steam coal C			Ash content exceeding 8%

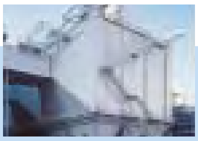

Power plant


Cement plant


Iron works


Chemical plant

Flue gas treatment


Electric precipitator


Flue gas denitration facility


Flue gas desulfurization facility

CO_2 reduction


Enhanced Oil Recovery (EOR) by CO_2

Effective coal ash use


Yokohama Landmark Tower

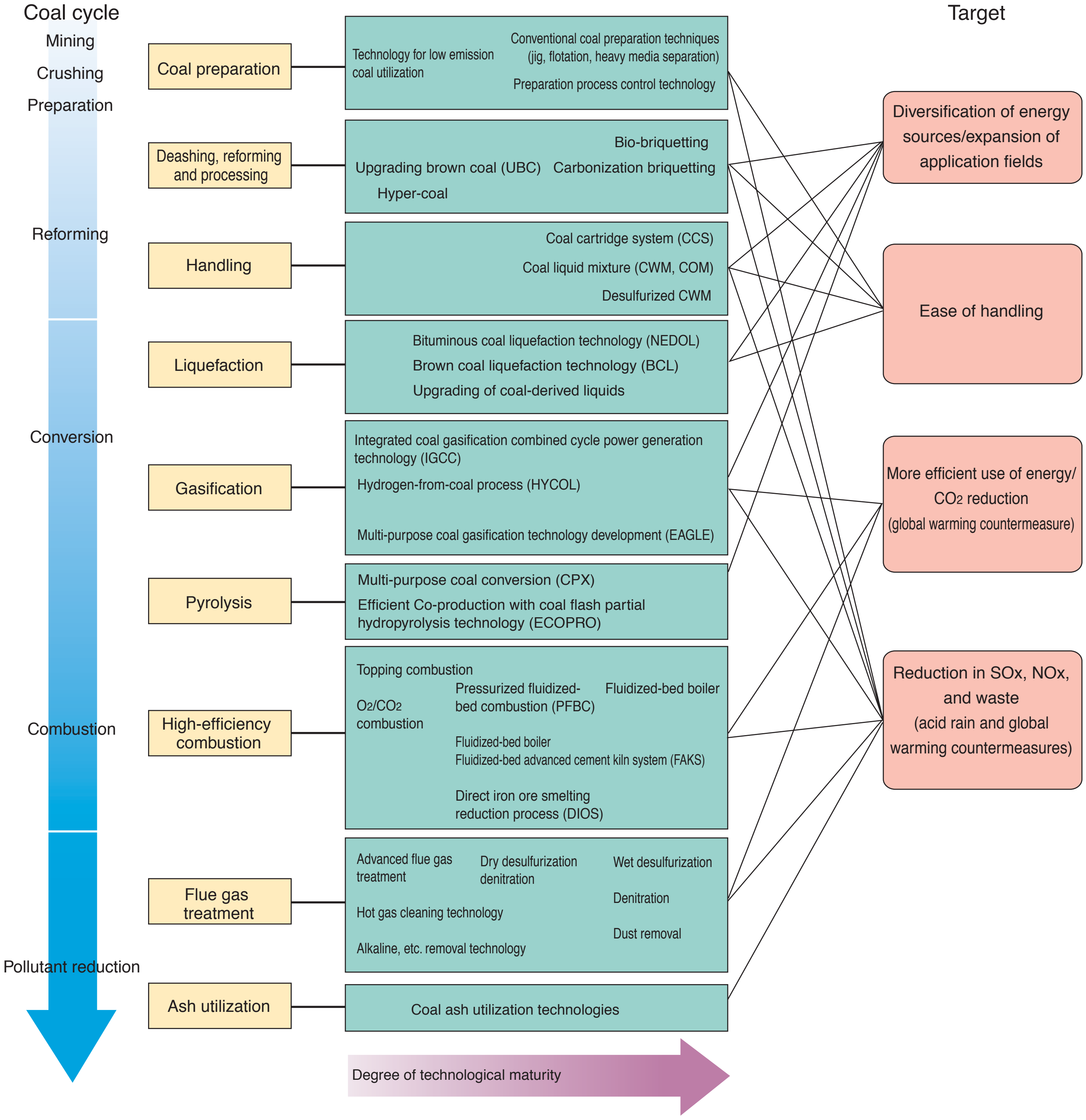
Utilization

- **High-efficiency Utilization Technologies**
  - **Coal-fired Power Generation Technologies**
    - **Combustion Technologies**
      - 2A1 Pulverized Coal-fired Power Generation Technology (Ultra Super Critical Steam Condition)
      - 2A2 Circulating Fluidized-bed Combustion Technology (CFBC)
      - 2A3 Internal Circulating Fluidized-bed Combustion Technology (ICFBC)
      - 2A4 Pressurized Internal Circulating Fluidized-bed Combustion Technology (PICFBC)
      - 2A5 Coal Partial Combustor Technology (CPC)
      - 2A6 Pressurized Fluidized-bed Combustion Technology (PFBC)
      - 2A7 Advanced Pressurized Fluidized-bed Combustion Technology (A-PFBC)
      - 4D1 Hyper-coal-based High-efficiency Combustion Technology (Hyper-coal)
    - **Gasification Technologies**
      - 2B1 Hydrogen-from-Coal Process (HYCOL)
      - 2B2 Integrated Coal Gasification Combined Cycle (IGCC)
      - 2B4 Integrated Coal Gasification Fuel Cell Combined Cycle Electric Power Generating Technology (IGFC)
      - 2B5 Next-generation, High-efficiency Integrated Coal Gasification Electric Power Generating Process (A-IGCC/A-IGFC)
  - **Iron Making Technologies**
    - 3A1 Formed Coke Process (FCP)
    - 3A2 Pulverized Coal Injection for Blast Furnaces (PCI)
    - 3A3 Direct Iron Ore Smelting Reduction Process (DIOS)
    - 3A4 Super Coke Oven for Productivity and Environment Enhancement toward the 21st Century (SCOPE21)
    - 3A5 Coke Dry Quenching Technology (CDQ)
  - **General Industry Technologies**
    - 3B1 Fluidized-bed Advanced Cement Kiln System (FAKS)
    - 3B2 New Scrap Recycling Process (NSR)
  - **Co-production Systems**
    - 7A1 Co-generation Systems
    - 7A2 Co-production Systems

Environmental countermeasures

- **CO_2 Recovery Technologies**
  - 5A1 Hydrogen Production by Reaction Integrated Novel Gasification Process (HyPr-RING)
  - 5A2 CO_2 Recovery and Sequestration Technology
  - 5A3 CO_2 Conversion Technology
  - 5A4 Oxy-fuel Combustion (Oxygen-firing of Conventional PCF System)
- **Flue Gas Treatment and Gas Cleaning Technologies**
  - 5B1 SOx Reduction Technology
  - 5B2 NOx Reduction Technology
  - 5B3 Simultaneous De-SOx and De-NOx Technology
  - 5B4 Particulate Treatment Technology and Trace Element Removal Technology
  - 5B5 Gas Cleaning Technology
- **Technologies to Effectively Use Coal Ash**
  - 5C1 Coal Ash Generation Process and Application Fields
  - 5C2 Effective Use of Ash in Cement/Concrete
  - 5C3 Effective Use of Ash in Civil Engineering/Construction and Other Applications
  - 5C4 Technology to Recover Valuable Resources from Coal Ash

Clean Coal Technology Systems



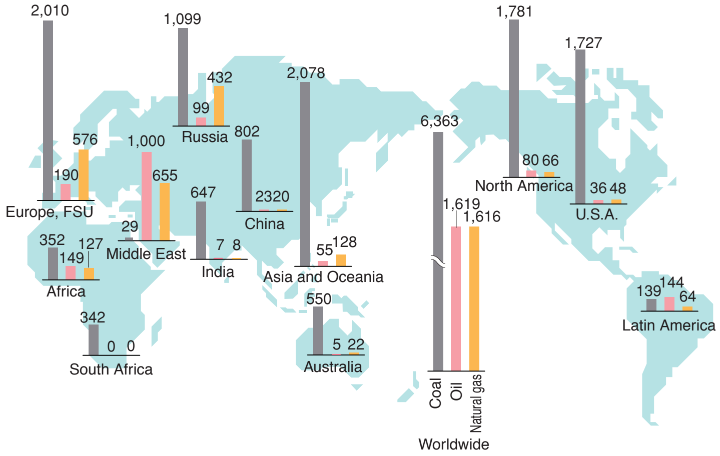
Proven reserves and R/P (ratio of reserves to production) of major energy resources

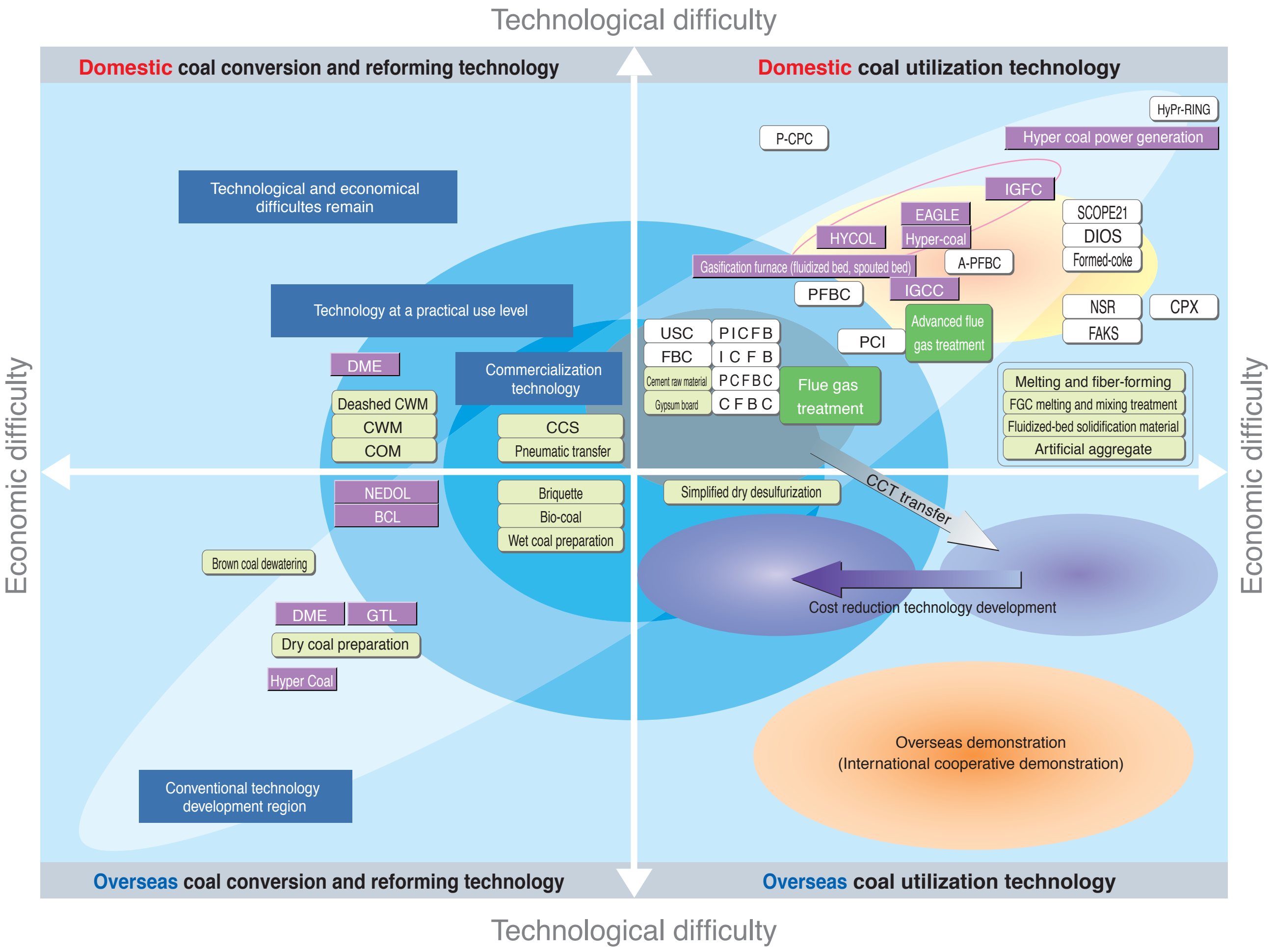
		Coal	Oil	Natural gas	Uranium
World reserves		9.091 trillion tons	1,188.6 billion barrels	180 trillion m^3	459 million tons
Local reserves	North America	27.8%	3.9%	3.9%	17.1%
	Latin America	2.3%	9.7%	4.2%	3.6%
	Europe	7.1%	1.6%	2.9%	2.8%
	Former Soviet Union	24.5%	10.0%	32.4%	28.7%
	Middle East	0.0%	61.7%	40.6%	0.2%
	Africa	5.6%	9.4%	7.8%	20.5%
	Asia Pacific	32.7%	3.5%	7.9%	27.2%
Annual production rate		5.54 billion tons	29.3 billion barrels (80.3 million B/D)	2.7 trillion m^3	0.036 million tons
R/P		164 years	40.5 years	66.7 years	85 years

Oil, natural gas, and coal data source: BP Statistics 2005
Uranium: OECD/NEA, IAEA URANIUM 2003

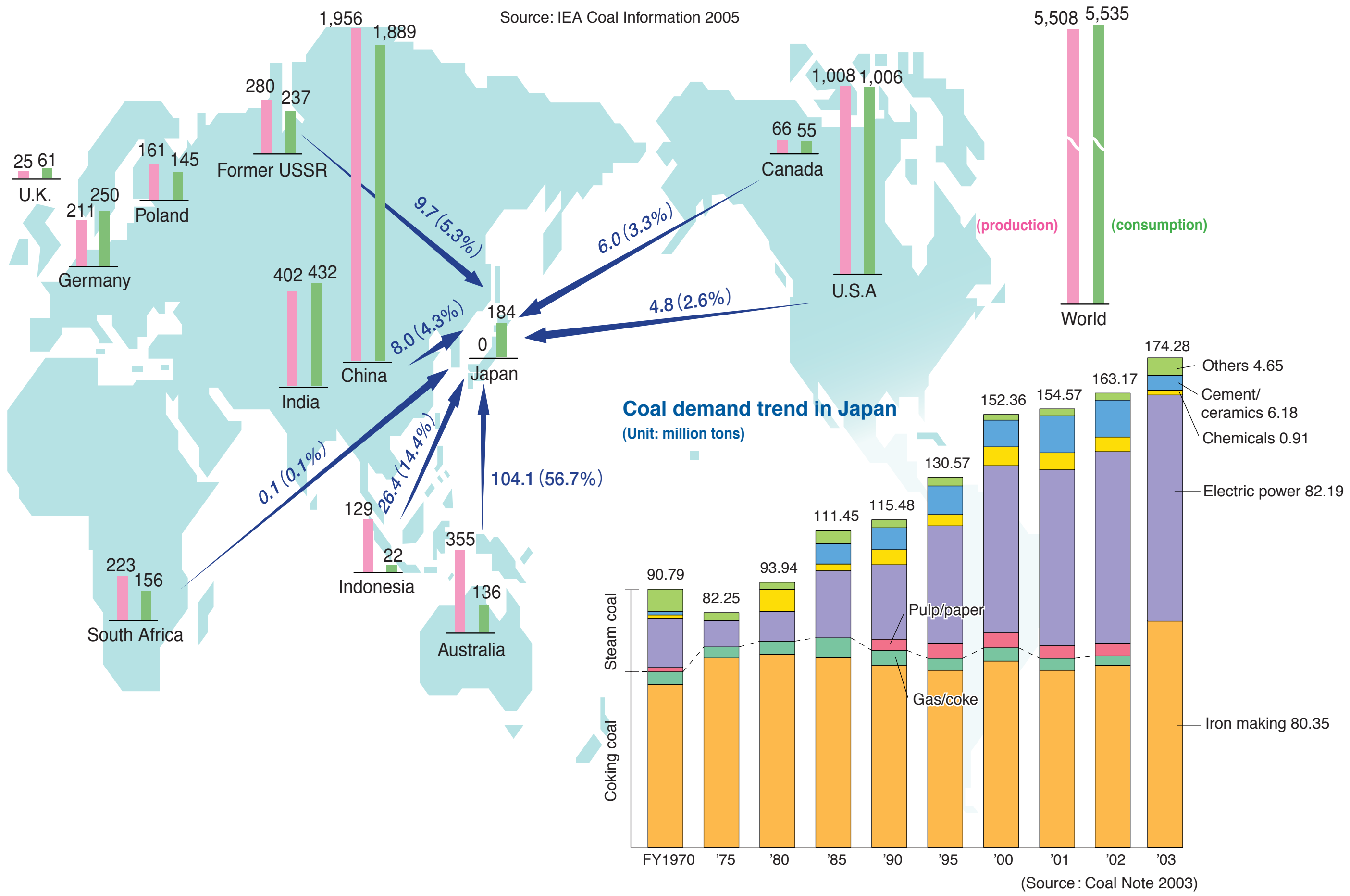
World reserves of coal, oil, and natural gas resources (Unit: 100 million tons oil equivalent)

(Source: BP 2005)



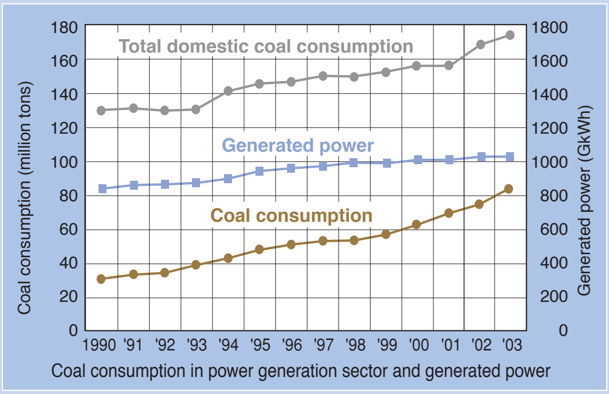


Coal Production and Consumption by Country in 2004 (Total coal production worldwide: 5.508 trillion tons; Total coal consumption worldwide: 5.535 trillion tons) and Japanese Coal Imports (Japan's total coal imports: 184 million tons)



(Source : Coal Note 2003)

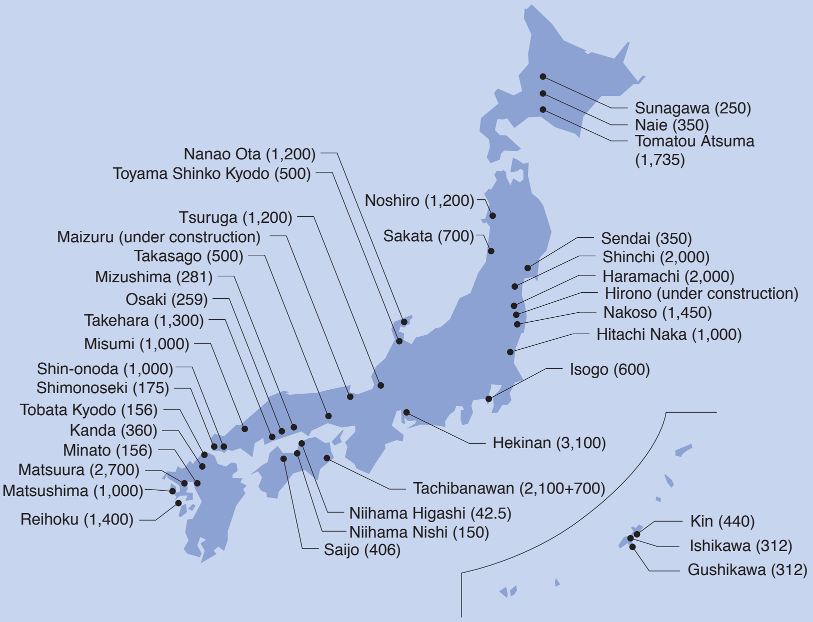
Power generation field



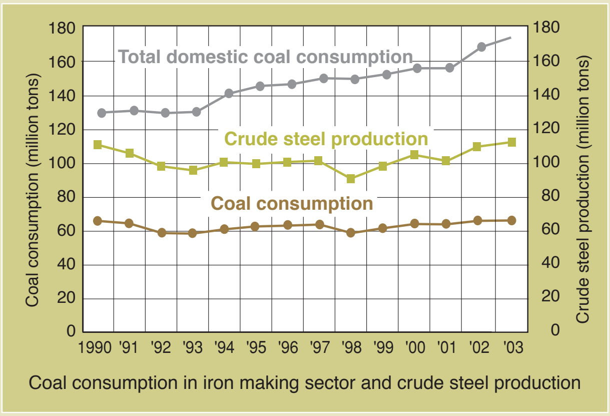
Coal consumption in power generation sector and generated power

Location of coal-fired power plants

Figures in parentheses indicate power generation capacity (MW) at the end of FY2005.



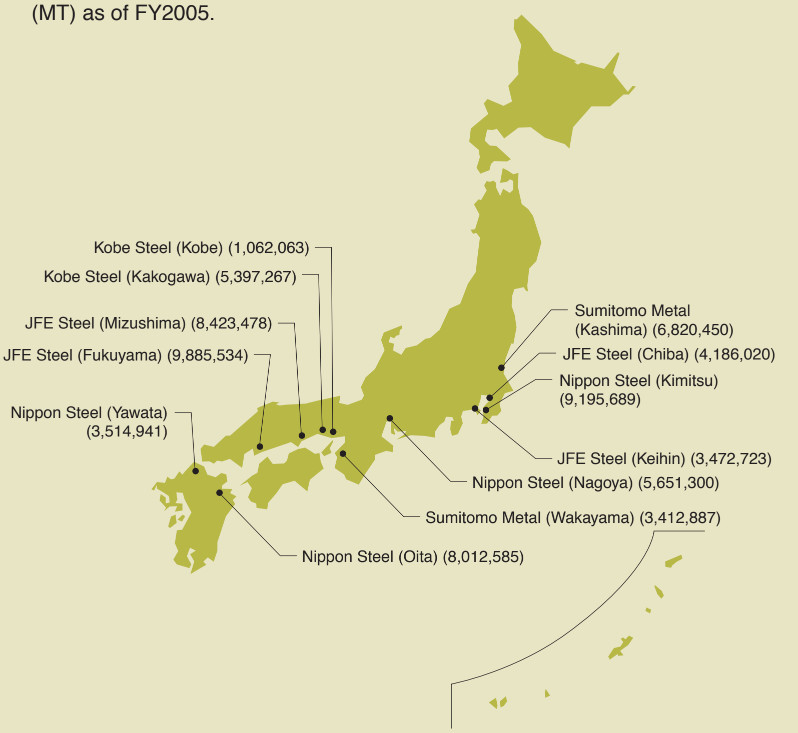
Iron making field



Coal consumption in iron making sector and crude steel production

Location of iron works

Figures in parentheses indicate crude steel production (MT) as of FY2005.



Coal-fired power generation technologies

2A1 Pulverized Coal-fired Power Generation Technology (Ultra Super Critical Steam)

2A2 Circulating Fluidized-bed Combustion Technology (CFBC)

2A3 Internal Circulating Fluidized-bed Combustion Technology (ICFBC)

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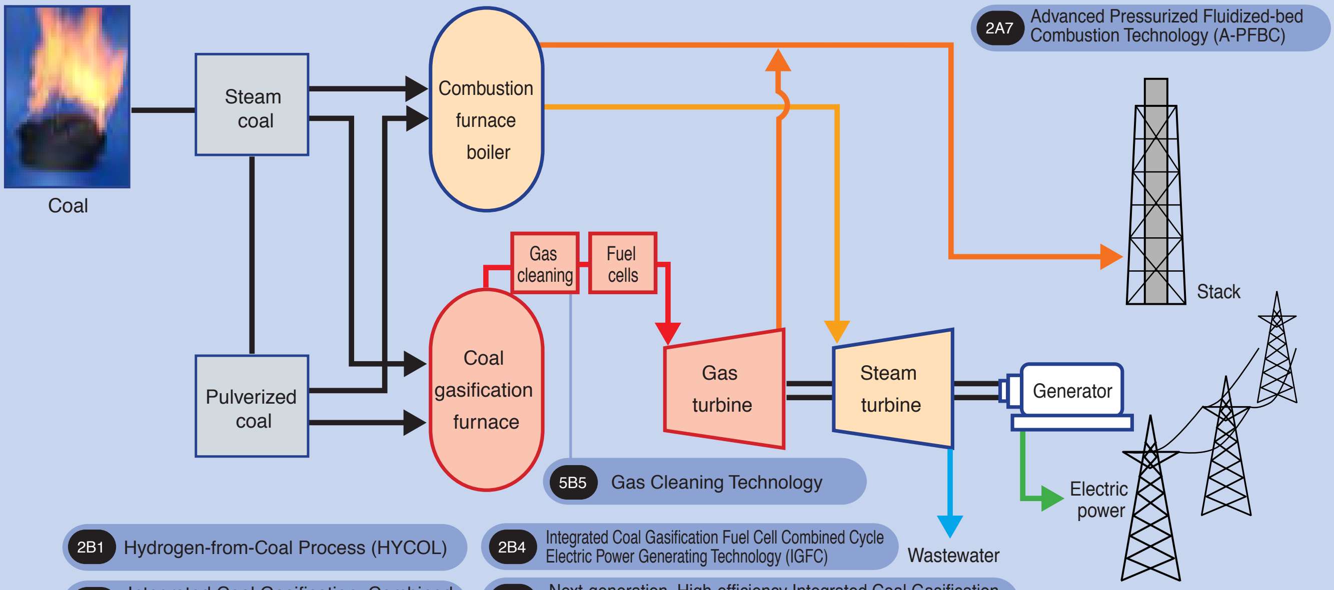
2A7 Advanced Pressurized Fluidized-bed Combustion Technology (A-PFBC)



5B5 Gas Cleaning Technology

2B1 Hydrogen-from-Coal Process (HYCOL)

2B2 Integrated Coal Gasification Combined Cycle (IGCC)

2B3 Multi-purpose Coal Gasification Technology Development (EAGLE)

2B4 Integrated Coal Gasification Fuel Cell Combined Cycle Electric Power Generating Technology (IGFC)

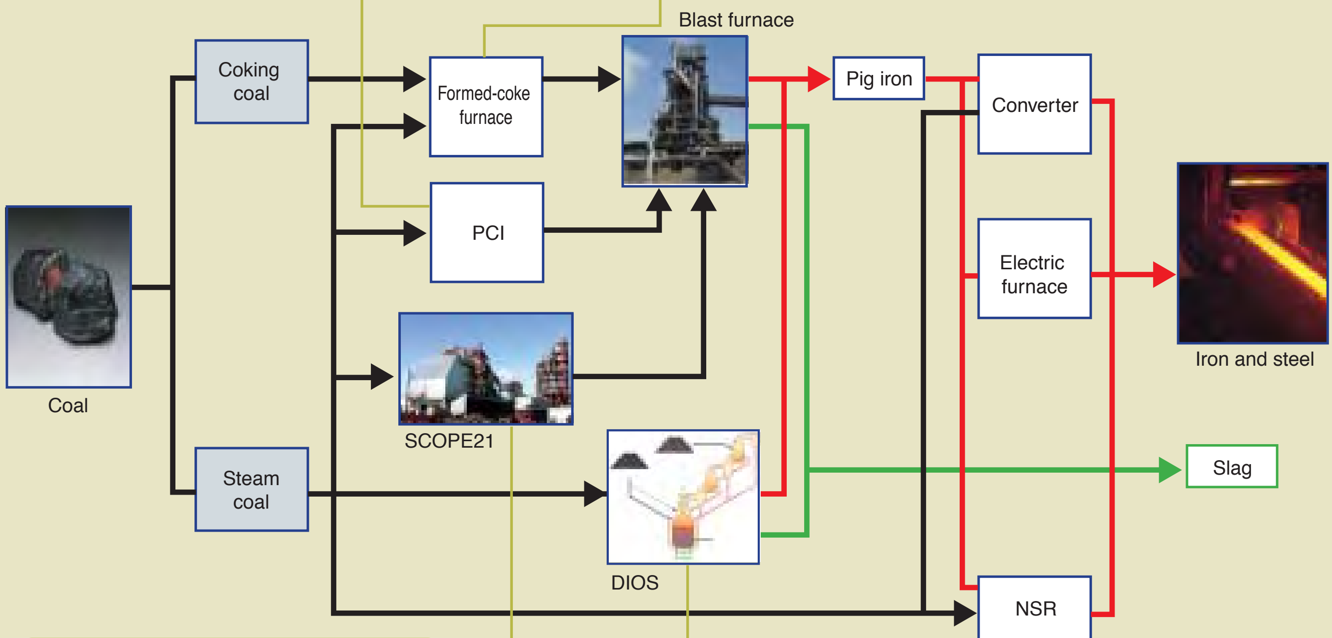
2B5 Next-generation, High-efficiency Integrated Coal Gasification Electric Power Generating Process (A-IGCC/A-IGFC)

4D1 Hyper-coal-based High-efficiency Combustion Technology (Hyper-coal)

Iron making technology

3A2 Pulverized Coal Injection for Blast Furnaces (PCI)

3A1 Formed Coke Process (FCP)



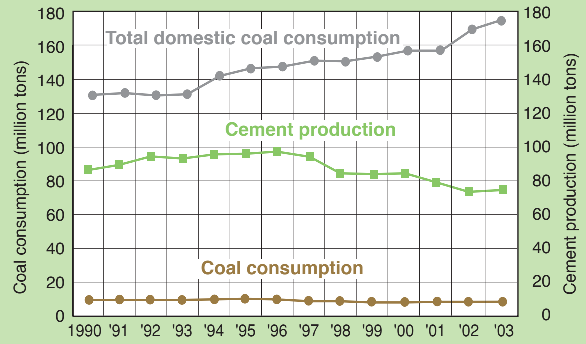
3A4 Super Coke Oven for Productivity and Environment Enhancement toward the 21st Century (SCOPE21)

3A3 Direct Iron Ore Smelting Reduction Process (DIOS)

3A5 Coke Dry Quenching Technology (CDQ)

3B2 New Scrap Recycling Process (NSR)

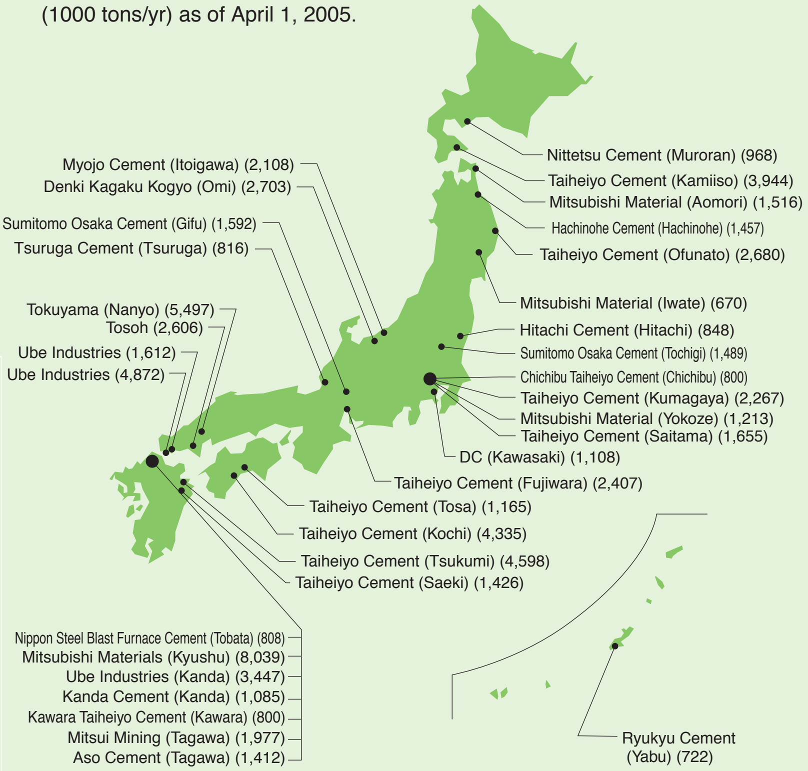
Cement production field



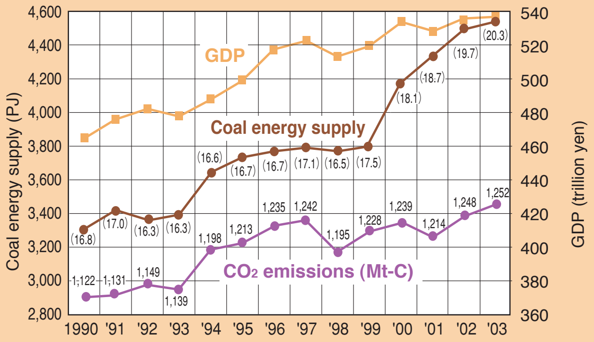
Coal consumption in cement production sector and cement production

Location of cement plants

Figures in parentheses indicate clinker production capacity (1000 tons/yr) as of April 1, 2005.



Coal chemicals and other fields

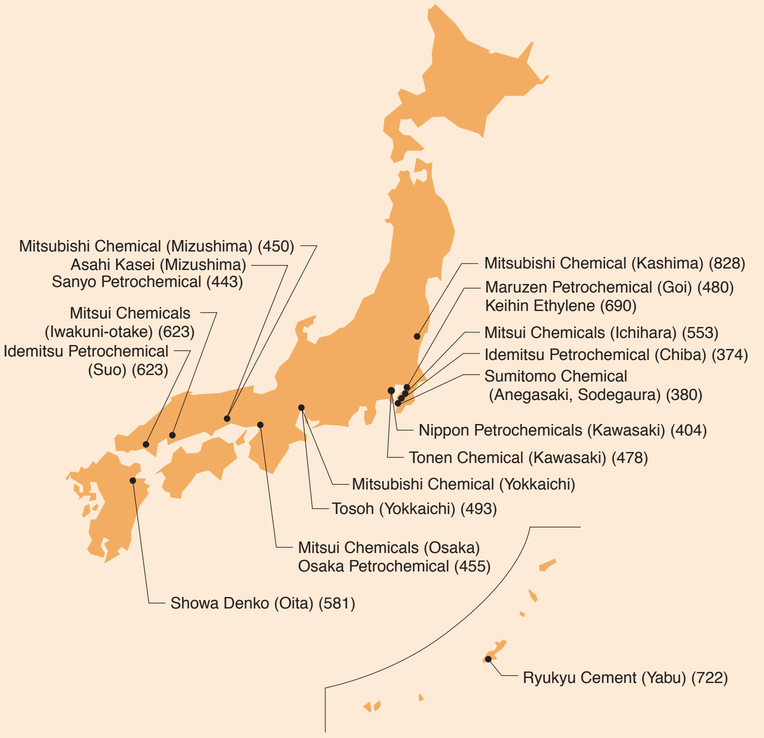


Coal energy supply, GDP, and CO_2 emissions in Japan

Figures in parentheses indicate coal's percentage of primary energy.

Location of chemical complexes

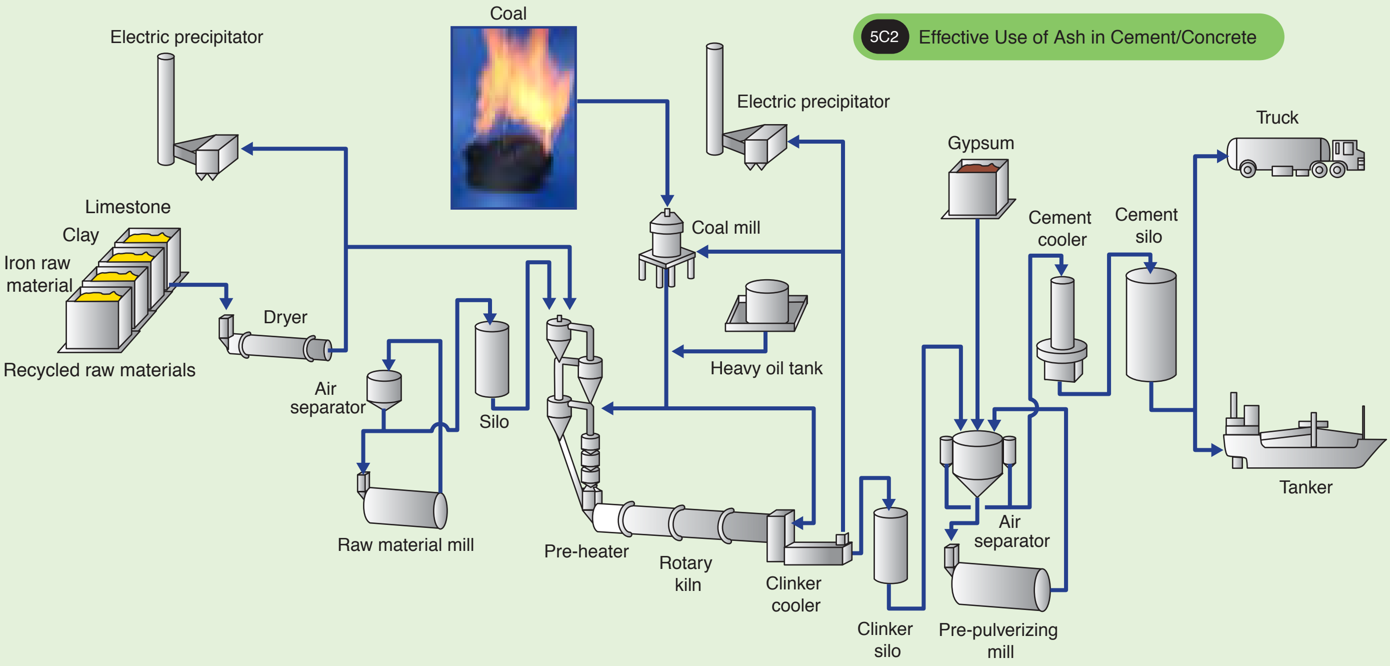
Figures in parentheses indicate ethylene production capacity (1000 tons/yr) at the end of FY2005.



Cement production technology

3B1 Fluidized-bed Advanced Cement Kiln System (FAKS)

5C2 Effective Use of Ash in Cement/Concrete



Coal chemical process

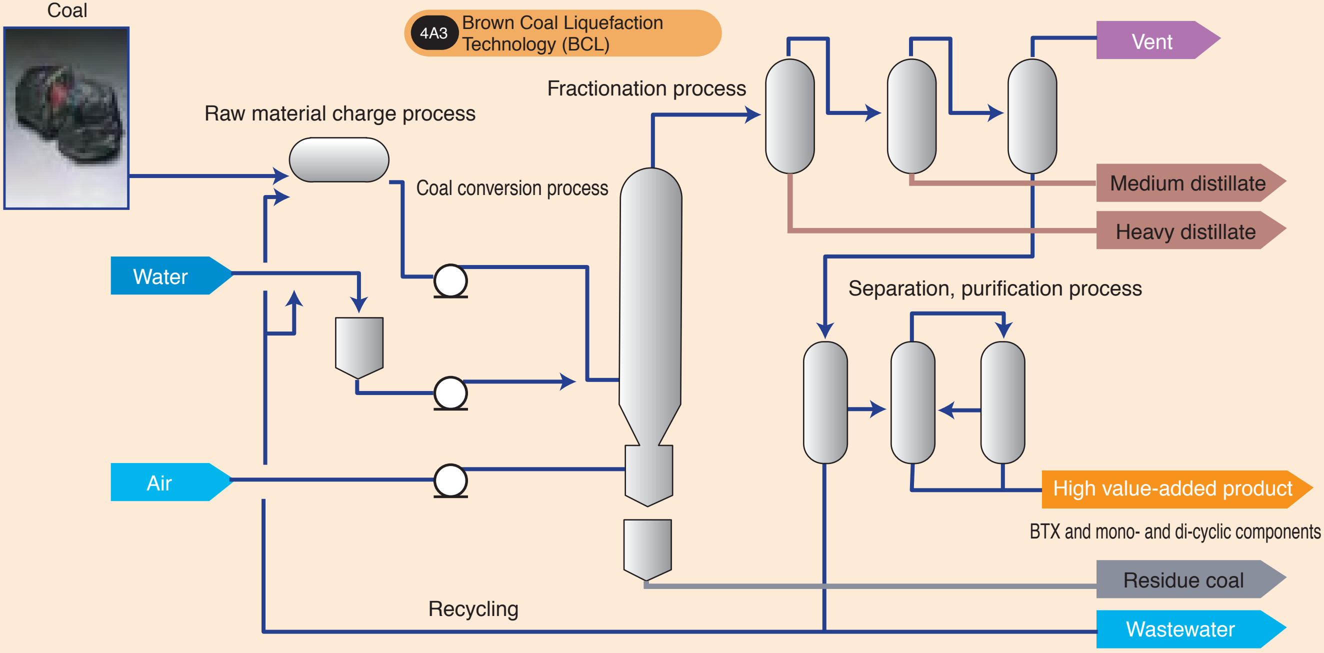
4A1 Coal Liquefaction Technology Development in Japan

4A2 Bituminous Coal Liquefaction Technology (NEDOL)

4A3 Brown Coal Liquefaction Technology (BCL)

4A4 Dimethyl Ether Production Technology (DME)

5A1 Hydrogen Production by Reaction Integrated Novel Gasification Process (HyPr-RING)



4B1 Multi-purpose Coal Conversion Technology (CPX)

4B2 Efficient Co-production with Coal Flash Partial Hydropyrolysis Technology (ECOPRO)

4D1 Hyper-coal-based High-efficiency Combustion Technology (Hyper-coal)

4D2 Low-rank Coal Upgrading Technology (UBC Process)

Efforts to reduce CO_2 emissions

The Kyoto Protocol, which requires Japan to reduce greenhouse gas emissions, including carbon dioxide, methane, nitrous oxide and alternative CFCs, by 6 percent from the 1990 level between 2008 and 2012, came into effect on February 16, 2005.

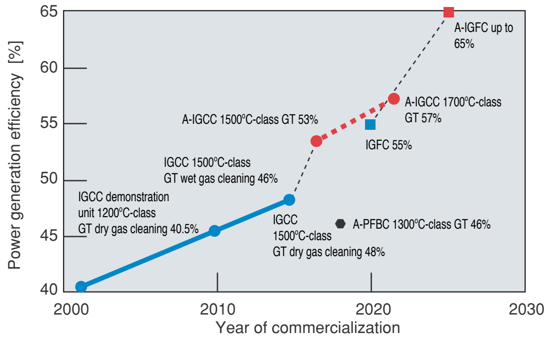
Among these global warming gases, carbon dioxide (CO_2) has the greatest impact on the environment. To reduce emissions of CO_2, Japan, with the most highly advanced clean coal technologies in the world, is promoting further technological developments, including:

[1] Reduction of CO_2 generation by enhancing coal utilization efficiency,
[2] Control of CO_2 emissions generated through direct coal burning by utilizing the carbon component in coal for material production, and
[3] Underground CO_2 sequestration and storage by decomposing and capturing CO_2 contained in flue gas.

Japan also promotes the reduction of CO_2 emissions through international cooperation using the Kyoto Mechanisms.

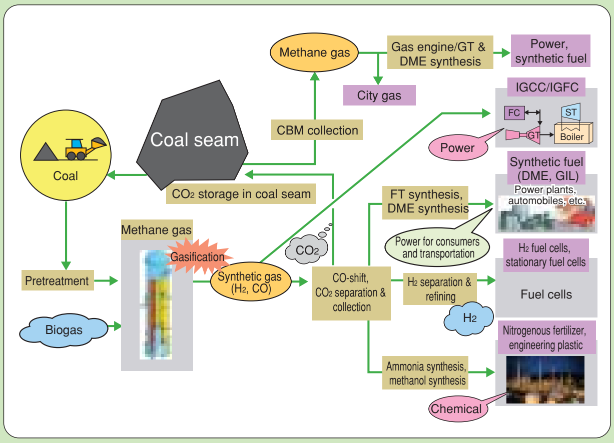
Energy-derived CO_2 emission trend in Japan

Source: CCT Journal Vol.11



Co-production

Source: JCOAL Journal, First issue

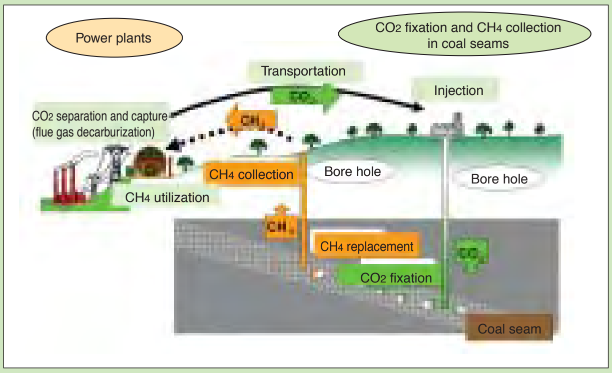


CO_2 capture and sequestration

Separation and capture
Chemical absorption
Physical adsorption
Membrane separation
Oxygen burning

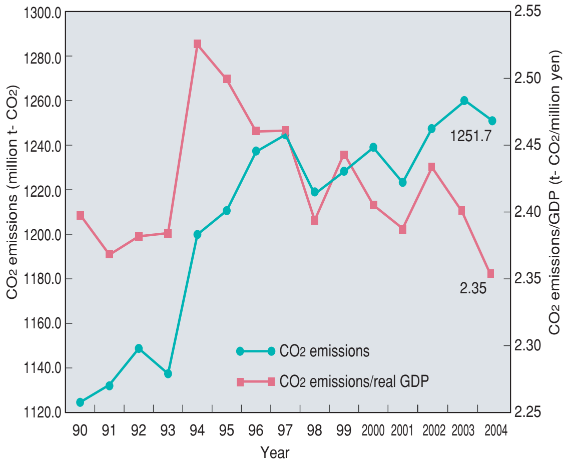
Transportation
Land: liquefied CO_2 pipelines
Marine: liquefied CO_2 transport ships

Capture and Sequestration
Underground: aquifer, coal seam
Ocean: dissolution, diffusion, hydride (on the sea floor)



Energy-derived CO_2 emission trend in Japan

Source: General Energy Statistics of Japan (2004 edition)



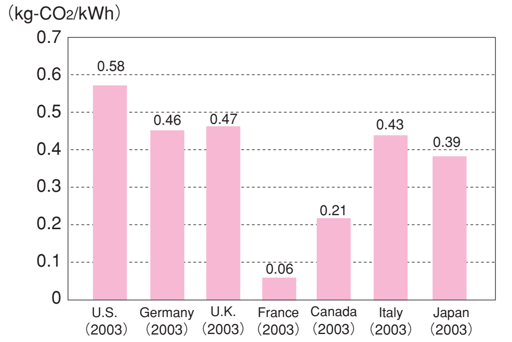
CO_2 emissions in major countries (million tons)

Source: IEO 2005

	1990	2001	2002	2010	2015	2020	2025
U.S.	4,989	5,692	5,751	6,561	6,988	7,461	7,981
Canada	473	573	588	681	726	757	807
Western Europe	3,413	3,585	3,549	3,674	3,761	3,812	3,952
Russia	2,347	1,553	1,522	1,732	1,857	1,971	2,063
China	2,262	3,176	3,322	5,536	6,506	7,373	8,133
India	583	1,009	1,025	1,369	1,581	1,786	1,994
Japan	990	1,182	1,179	1,211	1,232	1,240	1,242
World total	21,460	24,072	24,409	30,201	33,284	36,023	38,790

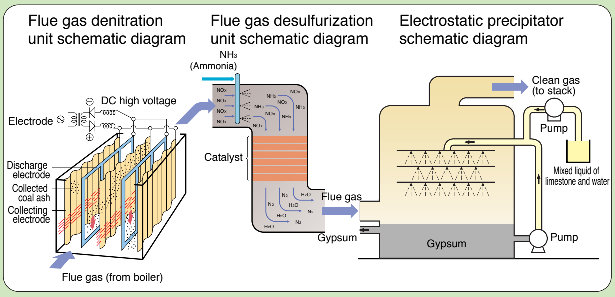
CO_2 emissions per generated power unit in major countries

Source: Federation of Electric Power Companies of Japan



Flue gas treatment technologies

Emission reduction technology to remove dust, sulfur oxides, and nitrogen oxides has been developed by treating and combusting flue gas from coal combustion through a superior process design.


Flue gas denitration unit schematic diagram

Flue gas desulfurization unit schematic diagram

Electrostatic precipitator schematic diagram

Electrostatic precipitator

Flue gas containing ash and dust passes between two electrodes that are charged by a high voltage current. The negatively charged ash and dust are attracted toward and deposited on the cathode. The ash and dust deposited on the cathode are tapped periodically, and are collected in the lower section of the electrostatic precipitator and then subsequently removed. The principle is the same as the phenomenon where paper and dust adhere to a celluloid board electrostatically charged by friction.

Flue gas desulfurizer

Limestone is powderized to prepare a water-based mixture (limestone slurry). The mixture is injected into the flue gas to induce a reaction between the limestone and the sulfur oxides in the flue gas to form calcium sulfite, which is further reacted with oxygen to form gypsum. The gypsum is then separated as a product.

Flue gas denitrizer

Ammonia is injected into the flue gas containing nitrogen oxides. The gas mixture is introduced to a metallic catalyst (a substance which induces chemical reactions). The nitrogen oxides in the flue gas undergo catalyst-induced chemical reactions, causing them to decompose into nitrogen and water.

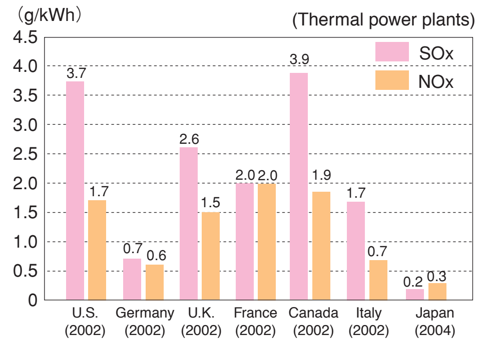
Reaction formulae

$$\underset{\text{(Nitrogen monoxide)}}{4NO} + \underset{\text{(Ammonia)}}{4NH_3} + O_2 \rightarrow \underset{\text{(Nitrogen gas)}}{4N_2} + 6H_2O$$

$$\underset{\text{(Nitrogen dioxide)}}{6NO_2} + 8NH_3 \rightarrow \underset{\text{(Nitrogen gas)}}{7N_2} + 12H_2O$$

Emissions of SOx and NOx per generated power in major countries

Source; The Federation of Electric Power Companies of Japan



Coal preparation technologies

Reducing sulfur oxide emissions during coal utilization is an important environmental conservation challenge. Coal preparation is an environmental control technology that removes iron pyrite particles that may be a source of ash content or sulfur oxides before coal is used.


Flotation machine

Heavy media cyclone

Sludge coal collection and dehydration technologies

Coal preparation leaves an effluent containing pulverized coal. Releasing the effluent into rivers and streams without treatment may cause environmental problems. To resolve the issue, and to also make effective use of this resource, a high-efficiency sludge coal collection and dehydration technique is now under development.

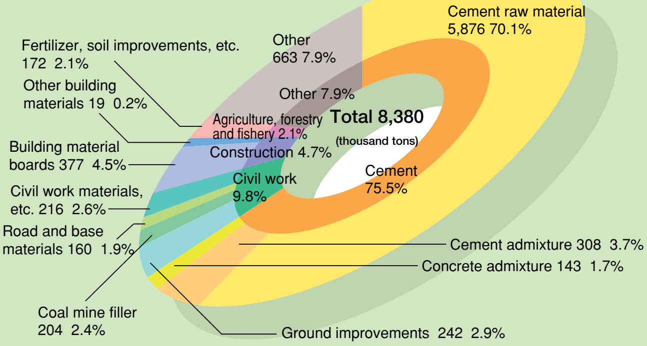

Effluent thickener

Dehydrator

Effective coal ash utilization technologies

Ash generated during coal combustion can be effectively used as a raw material for cement and other products. The use of ash for multiple purposes is under study.

Effective use of coal ash from power generation or general industries in Japan (FY2003)
Source: Survey report on actual usage of coal ash in Japan (JCOAL)



Current State of International Cooperation

Concomitant with the progress of industrialization and urbanization, developing countries are now facing serious air and water pollution issues. Coal is utilized to produce a significant proportion of the energy consumed in developing countries, particularly in Asia. As their economies have developed, it has become an increasingly significant challenge for these countries to develop and disseminate coal utilization technologies, along with broad environmental conservation measures.

Unfortunately, insufficient capital, techniques and expertise limit how much developing countries can improve environmental conditions on their own. They require the assistance of international organizations and of industrialized countries, including Japan. Japan has therefore promoted international cooperation with a focus on the Green Aid Plan (GAP) with counterpart countries, including China, Indonesia, Thailand, Malaysia, the Philippines, India and Vietnam.

In recent years, the global warming issue has attracted intense international concern. Global warming is a serious problem for the future of the earth and humankind, and is closely related to human economic activity and its accompanying energy consumption. Thus, it is important to address environmental needs during the pursuit of economic development.

The Kyoto Protocol, adopted in Kyoto in December 1997 and which came into effect on February 16, 2005, includes the "Kyoto Mechanisms," an important instrument for international cooperation. One of the Kyoto Mechanisms, a market mechanism known as the Clean Development Mechanism (CDM), is a new international cooperation system that aims to reduce greenhouse gas emissions through cooperation between developed and developing countries. To address global environmental issues that have continued to worsen worldwide, developing countries are encouraged to maximize their self-help efforts toward improving the environment by stemming the increases in pollution and the worsening of global warming.

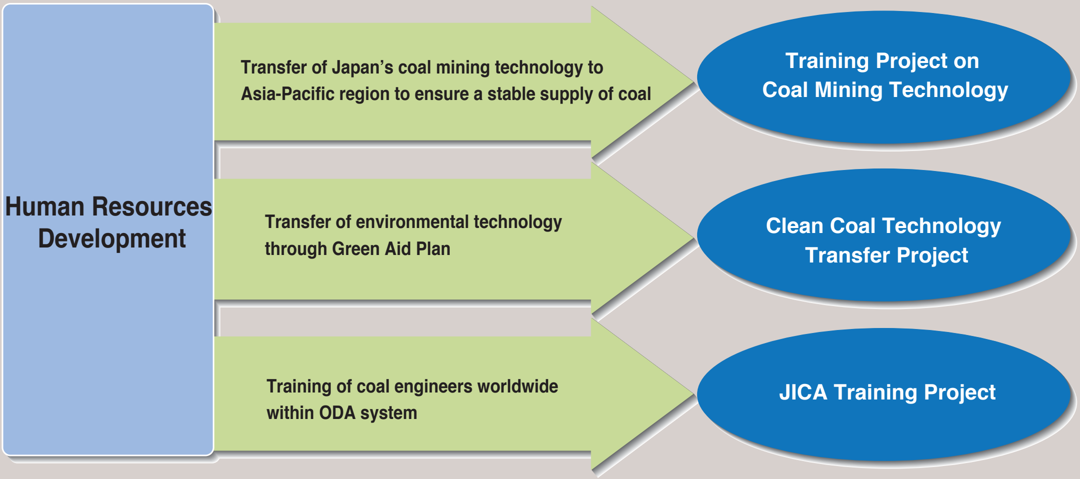
Japan has been encouraged to contribute to the economic growth and environmental improvement of developing countries through the active promotion of Japanese Clean Coal Technology (CCT) to Asian countries including China, which is expected to show a continued increase in coal demand. Japan also promotes technological cooperation with Australia in order to make coal a more effective energy resource with even greater cost efficiency and supply stability.

(1) Developing human resources

1) Training project on coal mining technology

Domestic mines have developed coal production and mine safety techniques with first-rate underground mining over a long period of time. Making use of these techniques, Japan provides technical cooperation to coal producing countries in the Asia-Pacific region to improve their coal production and mine safety. Japan also provides a human resource training project that accepts engineers from abroad and sends Japanese engineers to overseas coal-producing countries to ensure a stable supply of imported coal. Over 300 manager-level or higher ranking coal engineers from China, Indonesia and Vietnam have participated in the training program in Japan annually to receive face-to-face technical transfer sessions on business management, coal mining, mine safety and mechanical/electrical equipment at Japan's Kushiro mine and the Nagasaki Coal Mine Technology Training Center.

For overseas training, Japan sends coal engineers to China to provide seminar-style training, and sends coal engineers to Indonesia and Vietnam to provide direct guidance on-site at local mines.



2) Promoting dissemination of clean coal technology

For the purpose of promoting the dissemination of clean coal technology, improving coal utilization technology and deepening the understanding of these technologies, Japan promotes technical transfers on coal utilization and quality management, including pollution countermeasures to reduce SOx, NOx and dust emissions, as well as the promotion of high-efficiency power generation to improve energy usage efficiencies, by inviting engineers from APEC countries to participate in training programs in Japan.

3) Supporting JICA training projects

JCOAL supports or carries out coal-related projects and training programs supported by the Japan International Corporation Agency (JICA). JCOAL also provides domestic training programs on coal mining and mine safety techniques to engineers from Indonesia and Vietnam.

(2) List of clean coal technologies and model projects relating to GAP

List of clean coal technologies and model projects relating to GAP

Project name	Project period	Target country	Site	Counterpart
Post-combustion cleaning				
Simplified desulfurization unit	FY1993-FY1995	People's Republic of China	🔴 Weifang Chemical Plant 🔴 Nanning Chemical Industrial Group ⚫ Changshou Chemical Works	The State Planning Commission/Ministry of Chemical Industry The State Planning Commission/Ministry of Chemical Industry The State Planning Commission/Ministry of Chemical Industry
	FY1995-FY1997	Thailand	⚫ The Union Paper Public Co., Ltd.	Department of Industrial Works, Ministry of Industry
	FY1998-FY2001	People's Republic of China	🔴 Hunan Province Xiang Jiang Nitrogenous Fertllizer Industrial Co.,Ltd.	The State Development Planning Commission/State Administration of Petrochemical Industry/Hunan Provlncial Planning Commission
Coke oven gas desulfurization unit	FY1999-FY2002	People's Republic of China	🔴 Anyang Iron and Steel Group Co., Ltd.	The State Development Planning Commission/Henan Provlncial Planning Commission/The State Administration of Metallurgical Industry
Cleaning during combustion, improvement of combustion efficiency				
Circulating fluidized bed boiler	FY1993-FY1995	People's Republic of China	🔴 Fangshan Garment Group Co. 🔴 Lingzi Coal Mine Zibo Mining Administration	The State Planning Commission/Beijing Planning Commission The State Planning Commission/Ministry of Coal Industry
		Philippines	🔴 Batangas Coal-fired Thermal Power Plant	Department of Energy
	FY1995-FY1997	Indonesia	🔴 PT. Kertas Basuki Rachmat	Agency for the Assessment and Application of Technology (BPPT)
		People's Republic of China	🔴 Chaili Colliery, Zaozhuang Coal Mining Administration	The State Planning Commission/Ministry of Coal Industry
	FY1996-FY1998	People's Republic of China	🔴 Jinzhou Heat-power General Co.,Ltd.	The State Planning Commission/Planning Committee of Liaoning Provincs
	FY1996-FY1999	People's Republic of China	🔴 Zhejiang Huba Corporation	The State Planning Commission/Zhejiang Provincal Planning Commission
	FY1997-FY1999	Thailand	🔴 Saraburi factory of Indorama Chemicals (Thailand) Ltd.	Department of Industrial Works, Ministry of Industry
	FY1997-FY2001	People's Republic of China	🔴 Liaoyuan City Heating Power the Source of Energy Co.	The State Planning Commission/Jilin Provinclat Planning Commission
Pre-combustion cleaning				
Briquette production unit	FY1993-FY1995	People's Republic of China	🔴 Tangzhuang Mine of Linyi Coal Mine Administration	The State Planning Commission/Ministry of Coal Industry
		Indonesia	🔴 Tanjung Enim Mine	Ministry of Mines and Energy
	FY1996-FY1998	Indonesia	🔴 PT. Alas Wiratema Briket	Ministry of Mines and Energy
	FY1997-FY1999	Thailand	🔴 Electricity Generating Authority of Thailand Mae Moh Mine	Department of Industrial Works , Ministry of Industry
	FY1998-FY2002	Philippines	🔴 Filipines Systems Inc.	Department of Energy
Water-saving coal preparation system	FY1994-FY1997	People's Republic of China	⚫ Wangfenggang Coal Preparation Plant of Huainan Coal Mining Bureau ⚫ Preparation Plant of Dongtan Coal Mine of Yanzhou Coal Mining Bureau	The State Planning Commission/Ministry of Coal Industry The State Planning Commission/Ministry of Coal Industry
Desulfurization-type CWM unit	FY1995-FY1998	People's Republic of China	🔴 Beijing Yanshan Petrochemical Corp.	The State Planning Commission

🔴: project of Center for Coal Utilization, Japan ⚫:project of other organizations

1A1. Coal Reserve Exploration Technology

Technology Overview

1. Background

Coal is an important energy resource, responsible for producing 20% of the primary energy supply in Japan. However, 99% of the coal utilized is imported. To promote the sustainable development of coal resources in coal-producing countries and regions with a high potential for coal production, geological surveys, information analysis and evaluations from a variety of perspectives are important to ensure a stable energy supply. Coal reserve exploration technologies have become more precise and the imaging has been improved to provide higher resolution. For example, coal seams that occur under a high-density stratum can now be detected with higher resolution imaging. Also, a technology that allows direct estimation of ash and sulfur content in coal during geophysical logging has been studied. It is therefore important to establish a coal reserve assessment system, based on drilling or other exploration technologies, that will directly contribute to coal resource development and production plans, with a view to lessening the burden on both the local and global environment.


Image of high-resolution, high-efficiency survey system

2. Technology overview

Coal reserve assessment technologies being adopted for overseas coal-producing countries, (e.g. a joint coal resource evaluation survey in Indonesia and joint coal exploration in Vietnam) are to be improved, in addition to the promotion of environmental technologies for global warming prevention, including methane gas recovery in coal mines, carbon dioxide sequestration in coal seams and mine reclamations.

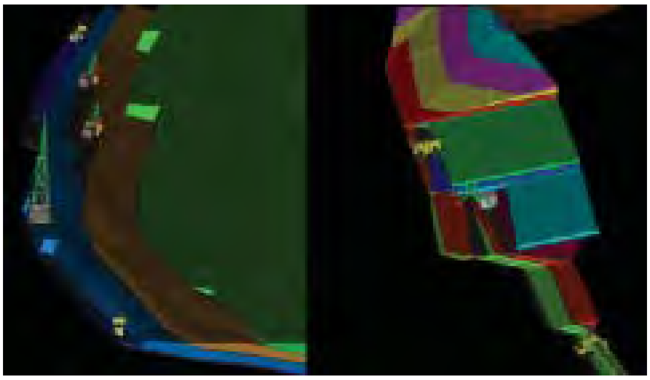
Resource exploration

[1] Through a joint study with the Ministry of Energy and Mineral Resources in Indonesia, GIS (Geographic Information Systems)-related technologies have been introduced to south Sumatra to digitize coal resource data, and to build a resource information database to allow general coal resource assessments as well as the development of an integrated software program.

[2] As part of a joint study with the Vietnam National Coal and Minerals Group (VINACOMIN), deep sounding is being carried out on the Quang Ninh coal basin in northern Vietnam for underground mining and coal development.

[3] Through a joint project with Mongolia's Ministry of Industry and Trade, coal resource exploration is currently being conducted in the Eastern Gobi, where the existence of a potential coal supply is anticipated.

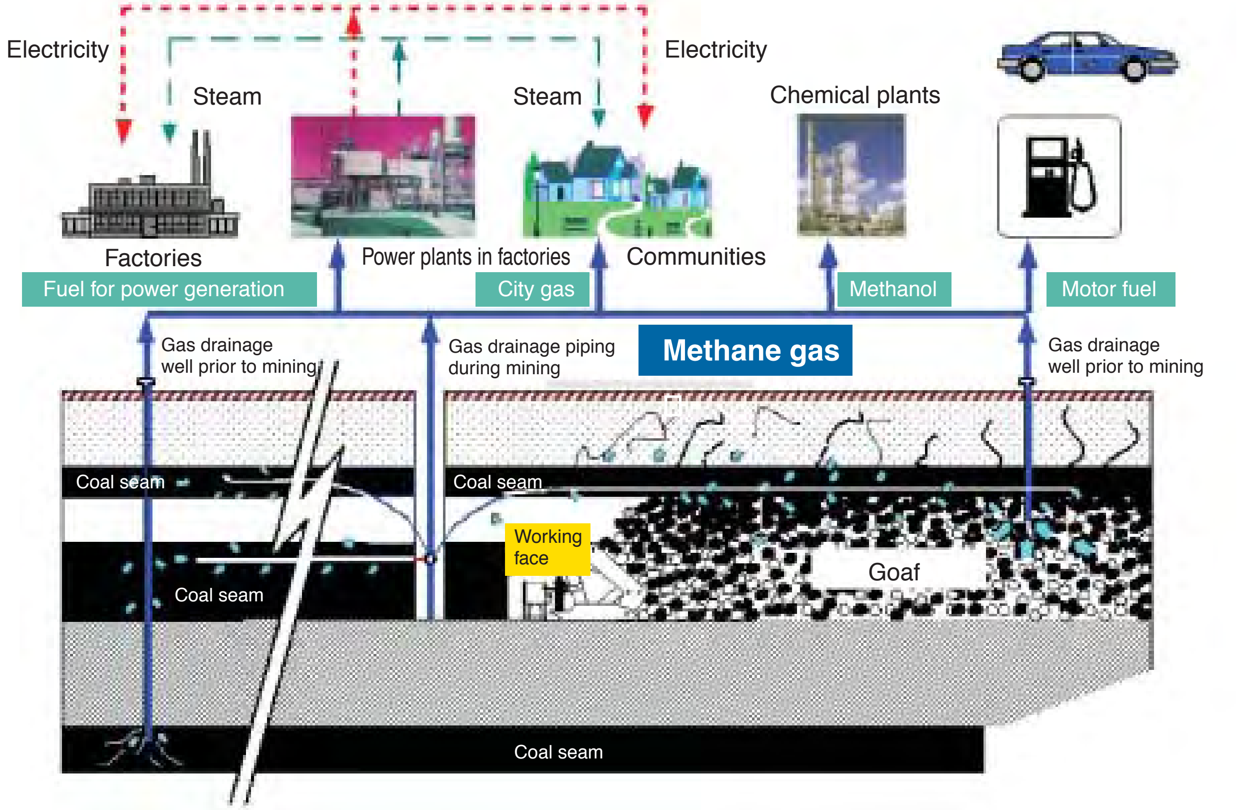
Coal resource evaluation system



Decision support system for coal development

Geological survey

Drilling survey in Indonesia



Collection and utilization of methane gas from coal mines

1A2. Coal Production Technology

Technology Overview

Coal occurs in slightly or steeply dipped beds, or in the form of discontinuous lenses underground. The depth, number and thickness of coal seams vary by region. Coal mine development requires consideration of these geological conditions and the state of ground surfaces. Specifically, the quality of coal, the depth, thickness and dip of coal seams, the presence of faults and folds, and the properties of coal-bearing strata substantially affect the productivity and the resource collection rate. The mining method to be used may also vary due to these conditions. Underground mining requires the drilling of shafts down to an underground coal seam to extract coal. The shafts may also be used to transport equipment and workers, for ventilation and drainage, or for prospecting for coal. As mining develops, the digging area becomes deeper, raising the issues of maintaining the mining space, gas emissions, and water seepage due to higher ground pressure. The mining machinery is required to have maneuverability to respond to variations in natural conditions. Utilizing larger-scale mining machinery to increase the extraction capacity of the equipment is limited by space constraints.

For mining coal deposits near the ground surface, open-cut mining is used to strip the overburden and extract the coal. When coal deposits are steeply dipped or composed of several coal seams, open-cut mining is used for extraction. In this mining method, the overburden is piled in a place where it will not interfere with the mining work, and a pit is formed in the ground surface during mining. Horizontal or slightly dipped coal deposits are mined by the strip mining (side casting) method, in which the overburden is temporarily piled just beside the mining site and returned to the original site after the coal has been extracted.

1. Background

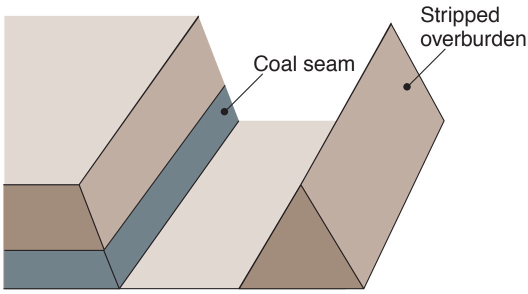
Coal-producing countries in the Asia-Pacific region are faced with coal mining challenges, such as mining under deeper and more complex geological conditions. To cope with these challenges, while improving safety and productivity, new technical measures are required. NEDO and JCOAL have, therefore, carried out domestic and international research and development on coal production based on technologies introduced and developed in Japan to improve mine safety and productivity while addressing the challenges faced by coal-producing countries. These efforts have led to the establishment of stable coal production systems and improved production capability, thus contributing to a stable supply of coal for Japan. Japan has also extended assistance to coal-producing developing countries for the sound development of local coal industries through joint research with local organizations, aimed at improving coal production technology.

2. Technologies to be developed

To address the challenges faced by coal-producing countries in the Asia-Pacific region, such as mining under complex geological conditions while ensuring safety, improved productivity, and a stable coal supply, novel technical measures are required.

(1) Open-cut mining
- Draglines
- Power shovels and dump trucks
- Overview of open-cast mining
- Side-cast O/C

Overview of typical open-cut mining



Side-cast strip mining

Draglines

Power shovels & dump trucks

(2) Underground mining
- Longwall mining
- High-power coal mining machines
- Highwall mining (auger mining)

Underground mining (headframe)

Development of a high-power coal mining machine

In order to achieve higher production efficiency in mining hard and thick coal seams, a new high-power multi-motor coal mining machine was demonstrated at a mine in Australia.

Longwall mining (SD Mining) drum shearer and shield support

High-power coal mining machine (following control function)

Highwall mining (steep incline auger mining system)

Development of a high-power excavator

To improve the efficiency of hard-rock tunnel boring, a high-power rock excavator equipped with rock bolts has been developed.

Drifting road header MRH-S220

Development of high-speed manned cars

In underground coal mining, as drifting progresses to include deeper working faces, measures are needed to ensure the necessary working time in the faces. To increase the efficiency of transportation and shorten the transportation time, high-speed manned cars with a maximum speed of 50 km/hr have been developed.

High-speed manned cars (former Taiheiyo coal mine)

High-speed manned cars (former Ikeshima coal mine)

1A3. Mine Safety Technology

Technology Overview

1. Background

According to the Mine Safety Technology Development and Long-term Technical Transfer Plan, the development of mine safety technology has been promoted with a focus on priority topics. Based on the results of this development, international joint research and technical cooperation/transfers have made considerable progress.

2. Technologies to be developed

(1) Applying mine safety technology to overseas mines

Japan applies its mine safety technology to model coal mines in coal-producing developing countries, thereby reducing mining disasters, improving mine safety and promoting stable coal production.

[1] In China, Japanese gas explosion disaster prevention techniques have been introduced to the Zhang-ji mine of the Huainan Mining (Group) Co. Ltd. in Anhui Province through the Central Coal Mining Research Institute. Specifically, the following four improvements were made: installation of a gas monitoring system, enhancement of gas drainage efficiency with directionally controlled gas drainage boring technology, introduction of underground ventilation analysis software and the installation of an underground radio system.

[2] In Indonesia, Japanese spontaneous combustion disaster prevention techniques have been introduced at the PTBA Ombilin mine through the Mineral and Coal Technology Research and Development Center (TekMIRA), including CO and temperature monitoring technology, gas analysis, underground ventilation network analysis and wall grouting.

[3] In Vietnam, Japanese mine water inflow disaster prevention technologies have been introduced to Mao Khe coal mine and other sites through the National Coal and Minerals Group (VINACOMIN), including hydrological data collection and analysis, underground water flow analysis using hydrogeological models, advanced boring technology for water exploration and drainage, and a flow rate measuring/pumping system.

(2) Joint research on mine safety technology

Through domestic development and international joint research with coal-producing developed countries, Japan promotes the development and sophistication of mine safety technology. This joint research will help further raise mine safety technology standards in both developing and developed coal-producing countries.

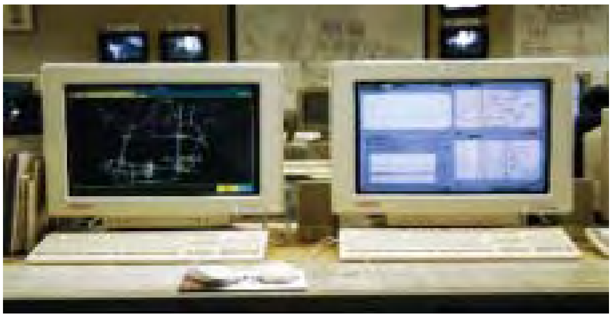
[1] Techniques to prevent roof fall accidents in roadways or at working faces have been developed, including roof fall risk prediction and roof fall prevention systems. These techniques are subjected to evaluation and applied to mine sites. For the purpose of developing systems, a site demonstration on long bolts was carried out at the Kushiro mine in Hokkaido. A series of basic site tests were also conducted at the same mine to collect measurement data on microtremors, roof/crack displacements, rock stress, acoustic characteristics and on elastic wave through the use of impact tests. Another study on roof fall prevention is underway to develop a system to identify roof conditions by analyzing machinery data during the drilling of rock bolt holes.

[2] With a view to developing comprehensive underground gas management technology, numerical analysis software, MGF-3D, which uses the stress variations that occur as digging proceeds, is being improved and subjected to model analysis. The software also has a gas-liquid, two-phase analysis function to improve analytical accuracy.

[3] An advanced monitoring and communications system for underground mine safety and stable production has been developed through joint research conducted with the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The system has now reached the stage of being applied to mine sites. This joint research also aims to build a basic system for risk information management that allows the real-time evaluation of different disaster risk factors (relating to work, environment, devices and machinery). As an early detection technique, an odor sensor based on worldwide standards is now being studied in a joint research project with the Safety in Mines, Testing and Research Station (SIMTARS). At the Kushiro mine, a "man location system" and an underground communications system were tested during an on-site demonstration.

Centralized monitoring and management technology

All underground mine safety information, including different measurement data items and the status of machine operations (both received and sent data), is controlled as a single unit by a computer system in a centralized monitoring and control room located on the surface.

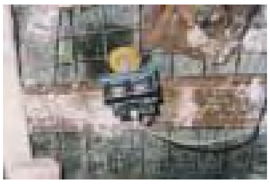


Centralized monitoring computers

Centralized monitoring and control room

Roadway support technique (rock bolting)

A rock bolting roadway support technique is based on rock mass evaluations and measurements to overcome Japan’s soft soil conditions.



Data transmitting roof displacement gauge

Bolt-supported roadway

Geostructure data logging

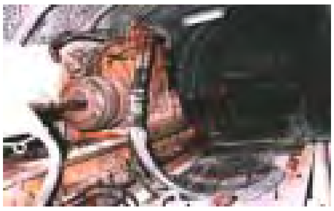
Technology to determine roof conditions by compiling machinery data during the drilling of bolt holes

Drilling

Gas drainage technology

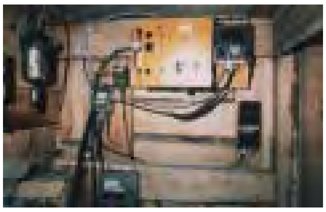
Gas drainage from coal seams and gobs is performed to prevent the emission of explosive methane gas.

The drainage is safely controlled in terms of volume and concentration using the centralized monitoring system.



Gas drainage boring

Gas drainage hole



Gas drainage monitoring sensors

Gas drainage monitoring computer

1A4. Environment-friendly Resource Development Technology

Technology Overview

1. Background

Through on-site demonstrations of carbon dioxide fixation in coal seams, the reservoir characteristics of coal seams in Japan were identified in order to collect basic data on carbon dioxide. In addition to conventional coal preparation and reforming, and CMM collection and utilization, efforts were made to study energy recovery through the underground gasification of coal resources, which may offer significant environmental benefits. The development and commercialization of CDM projects were also addressed.

2. Technologies to be developed

(1) Coal preparation and reforming technology

[1] Coal preparation technology is used in Indonesia to efficiently sort raw coal with different properties in order to ensure stable product quality and reduce the environmental burden. Japan manufactured part of the equipment necessary for improving existing coal preparation plants in Indonesia. To introduce jigging feedback control using on-line ash monitors to the coal preparation process in Indonesia, Japan formulated a control rule on a trial basis from the results of a feedback control applicability test.

[2] To promote the effective use of low-rank coal, a reforming plant using the upgrading brown coal (UBC) process (raw coal processing capacity: 5 tons/day) was subjected to test operations in Indonesia, where, compared to other countries, a relatively higher percentage of brown coal reserves exist. In the UBC process, low-rank coal is dehydrated in an oil slurry to stabilize it and make it water-repellent under moderate conditions. In the test plant, various types of Indonesian coal with different properties were tested. The data obtained was used for evaluation tests on spontaneous combustion, combustibility and other properties. It was ultimately confirmed that the reformed coal had handling properties and combustibility equal to or greater than those of bituminous coal.


Flotation machine

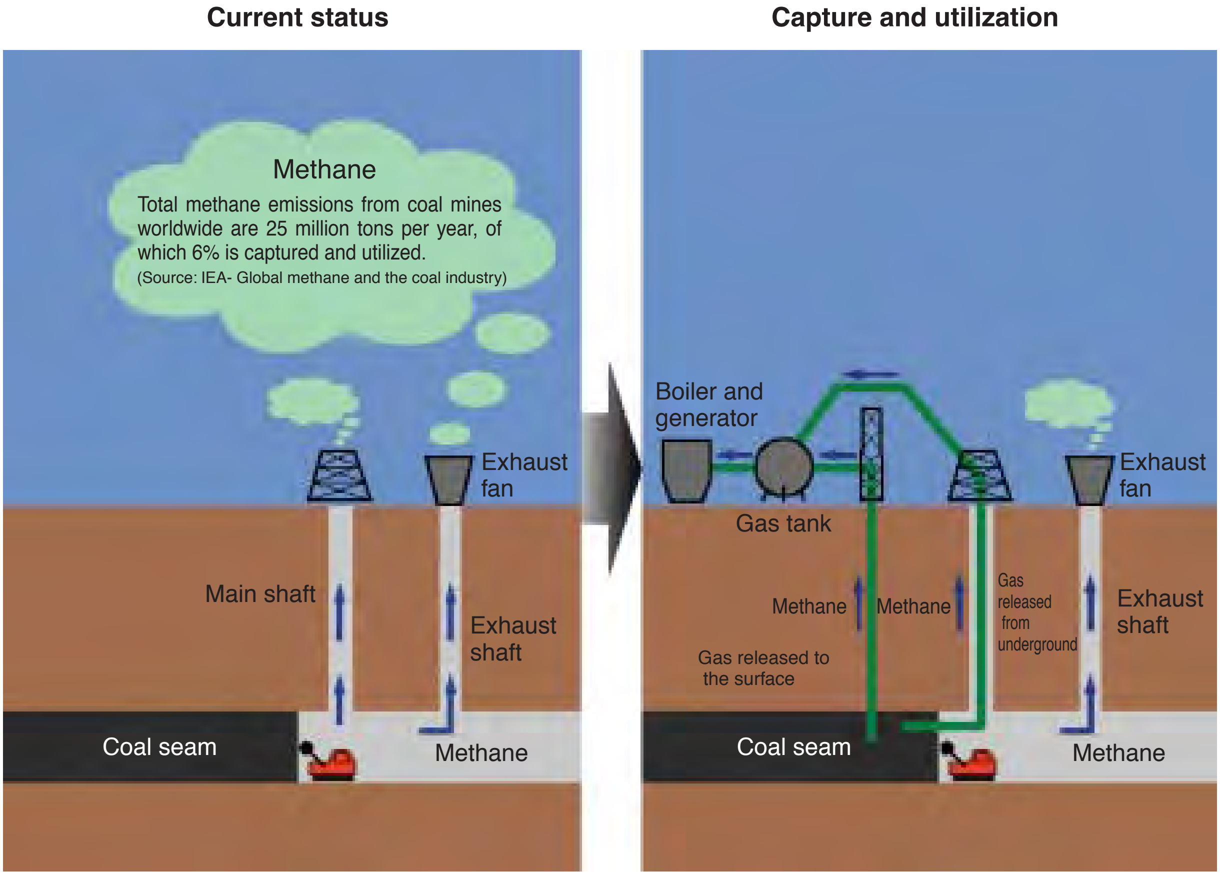

Heavy media cyclone


Effluent thickener

(2) Global environmental technology

[1] To suppress the release of carbon dioxide (CO_2) to the atmosphere, a preliminary test on a new technology to sequester CO_2 in deep coal seams has been conducted in the southern part of Yubari City in Hokkaido. The site injection test will be conducted through FY2006, aiming to successfully sequester CO_2 in PW-1, a methane gas observation well. Since the injection well IW-1, drilled in FY2003, is expected to have lower permeability due to CO_2 absorption and swelling, N_2 gas is injected to reduce CO_2 absorption and subsequently improve the permeability. N_2 gas is also used as a preliminary gas for CO_2 sequestration. CO_2 is injected at the maximum allowable pressure that will not induce the crushing of the coal seam. More than 900 tons of CO_2 are planned to be injected. Hydraulic fracturing tests of the coal seams are due to be conducted to improve gas injections and coal productivity.

[2] A site test of a technique for the stable collection and utilization of methane gas escaping from coal mines was carried out at an abandoned domestic mine in Hokkaido.



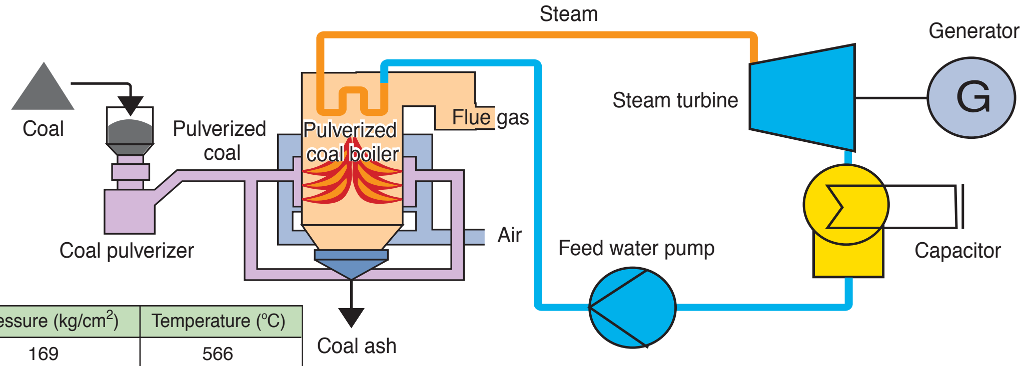
Conceptual drawing of coal mine methane gas capture and utilization

2A1. Pulverized Coal-fired Power Generation Technology (Ultra Super Critical Steam Condition)

Technology Overview

1. Pulverized coal-fired power generation system

The pulverized coal-fired power generation system (Fig. 1) is widely used as an established, highly reliable technology. In 2000, 600/610°C USC (Ultra Super Critical Steam Condition) systems were installed at J-POWER's Tachibanawan Thermal Power Station's No. 1 and No. 2 plants (1050 MW each). J-POWER's Isogo New Unit No. 1, which was put into service in 2002, uses the same system with pure voltage regulation at the main steam temperature of 600°C and the reheat steam temperature of 610°C. Further challenges will be to use more types of coal, increase generation efficiency, improve environmental measures and enhance load operability.



Steam conditions	Pressure (kg/cm^2)	Temperature (°C)
Subcritical	169	566
Supercritical	246	538
Ultra-supercritical	325	596

Fig. 1 Pulverized coal-fired power generation system (Rankine cycle)

2. Efficiency increase

Increasing the thermal efficiency of power generation plants is an important issue not only to decrease the power generation costs from an economic standpoint, but also for suppressing CO_2 emissions. In particular, steam temperatures at coal-fired power plants, which are currently the most prevalent among large thermal power plants, have increased. Figure 2 shows the trend of steam condition in recent years.

In 1989, Chubu Electric Power Co., Inc.'s Kawagoe No. 1 plant (700 MW) adopted the steam condition of 316 kg/cm^{2}g (31.0 MPa) x 566°C/566°C. In 1993, Chubu's Hekinan No. 3 plant (700 MW) adopted the steam condition of 246 kg/cm^{2}g (24.1 MPa) x 538°C/593°C, marking the highest reheated steam temperature in Japan. Subsequently, The Chugoku Electric Power Co., Inc.'s Misumi No. 1 plant (1000 MW) and Tohoku Electric Power Co., Inc.'s Haramachi No. 2 plant (1000 MW) adopted the steam condition of 24.5 MPa x 600°C/600°C in 1998. Furthermore, J-POWER's Tachibanawan No. 1 and No. 2 plants (1050 MW) adopted the steam condition of 25.0 MPa x 600°C/610°C in 2000. Figure 3 shows an example of the relationship between the steam condition and the efficiency of a supercritical pressure plant.

Responding to the trend of increasing steam temperatures, power companies, steel manufacturers, and boiler manufacturers are promoting the development and practical application of high-strength materials with superior high-temperature corrosion resistance, steam-oxidation resistance, and workability.

High-temperature materials for use at 650°C have already been introduced into practical application, with work proceeding to develop materials for use at 700°C.

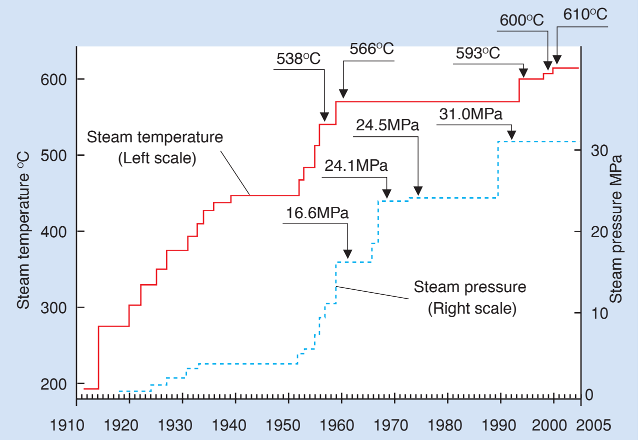


Fig. 2 Changes in steam condition over time

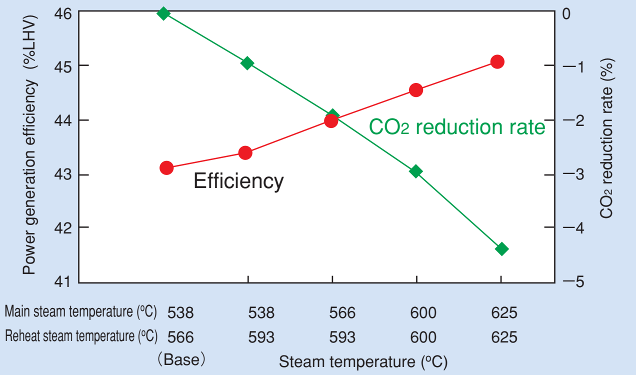


Fig. 3 Power generation efficiency and CO_2 reduction rate for various steam conditions

3. Combustion technology

Various combustion techniques have been developed and put into practical application in response to the need to satisfy Japan's strict environmental regulations, and to achieve high-efficiency combustion. The NOx emission level and the dust generated during the combustion of coal in Japan is at the world's lowest level, even at boiler exit. The ultimate emission level owes to the flue gas treatment administered at the downstream side of the boiler. Since NOx and dust emissions are very closely related, low NOx combustion technology is addressed here. Low NOx combustion technology is roughly classified according to the suppression of NOx generation at the burner and the intrafurnace denitration, using all the zones in the furnace.

(1) Low NOx pulverized coal burner

The latest burners have both improved ignitability and intraflame denitration, although the structure varies by boiler manufacturer. These burners basically use the separation of dense and lean pulverized coal streams and a multilayer charge of combustion air. Figures 4 to 7 show the burner structures of several Japanese manufacturers.

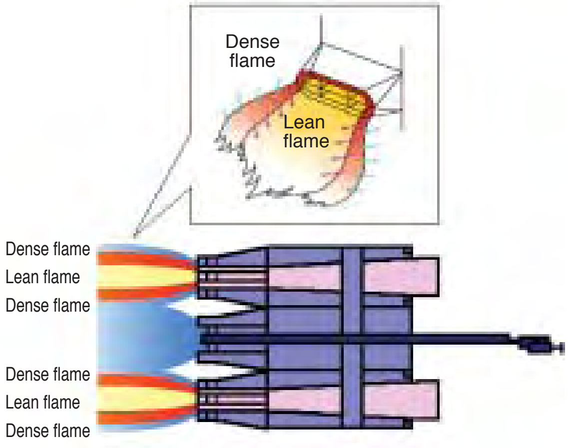


Fig. 4 Pulverized coal-fired A-PM burner: Mitsubishi Heavy Industries, Ltd.

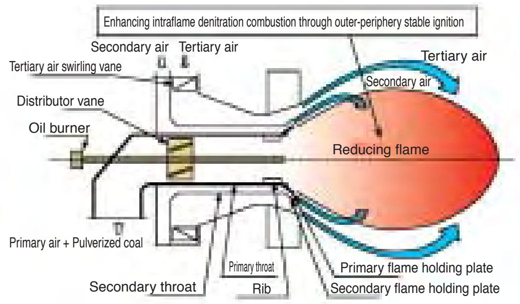


Fig. 5 CC-type pulverized coal-fired burner:
Kawasaki Heavy Industries, Ltd.

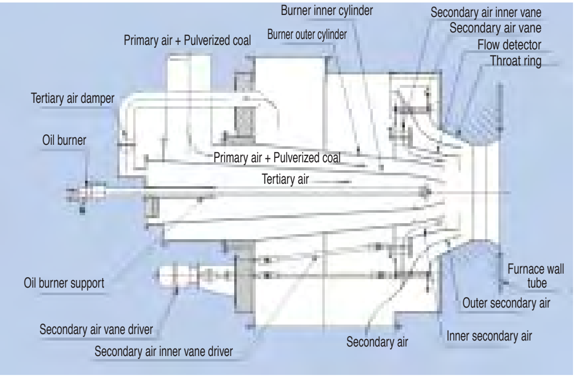


Fig. 6 DF inner vane pulverized coal-fired burner:
Ishikawajima-Harima Heavy Industries Co., Ltd.

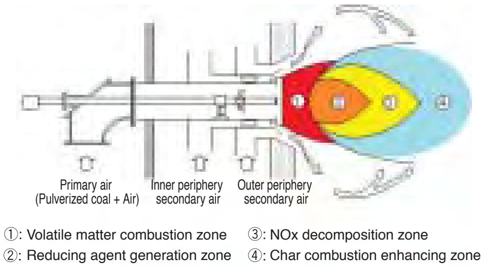


Fig. 7 Pulverized coal-fired NR burner: Babcock-Hitachi K.K.

(2) Intrafurnace denitration

Intrafurnace denitration is conducted by reducing the NOx generated in the main burner zone, using the residual hydrocarbons or the hydrocarbons generated from a small amount of fuel oil fed from the top of the main burner. The intrafurnace denitration is performed in two stages. Figure 8 is a conceptual drawing of intrafurnace denitration.

In the first stage, hydrocarbons reduce NOx levels. In the second stage, the unburned matter is completely combusted by the additionally injected air.

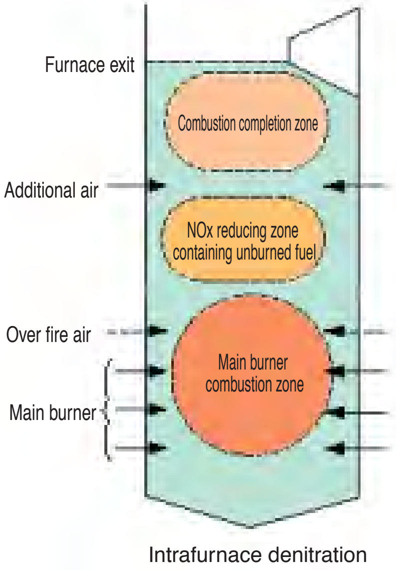


Fig. 8 Conceptual drawing of intrafurnace denitration

2A2. Circulating Fluidized-bed Combustion Technology (CFBC)

Technology Overview

1. Features

The features of circulating fluidized-bed boilers are described below.

1) Compatibility with wide range of fuels

Conventional boilers for power generation can use only fossil fuels, such as high-grade coal, oil, and gas. The CFBC is also capable of using low-grade coal, biomass, sludge, waste plastics, and waste tires as fuel.

2) Low polluting

NOx and SOx emissions are significantly decreased without special environmental modifications. In the case of fluidized-bed boilers, desulfurization is carried out intrafurnace, using mainly limestone as the fluidizing material. For denitration, PC boilers operate at combustion temperatures from 1,400°C to 1,500°C, whereas circulating fluidized-bed boilers operate at lower temperatures, ranging from 850°C to 900°C, thereby suppressing thermal NOx emissions as the generation of NOx is dependent upon the combustion temperature. In addition, the operation of circulating fluidized-bed boilers involves a two-stage combustion process: the reducing combustion at the fluidized-bed section, and the oxidizing combustion at the freeboard section. Next, the unburned carbon is collected by a high-temperature cyclone located at the boiler exit to recycle to the boiler, thus increasing the denitration efficiency.

3) High combustion efficiency

Improved combustion efficiency is attained through the use of a circulating fluidization-mode combustion mechanism.

4) Space-saving, ease of maintenance

Space saving is attained because there is no need for separate desulfurization, denitration, and fine-fuel crushing units. Accordingly, trouble-spots are minimized, and maintenance is simplified.

2. Technology overview

Figure 1 shows a typical CFBC process flow.

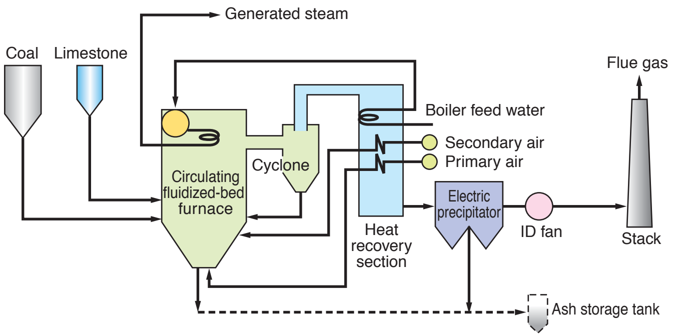


Fig. 1 Process flow of circulating fluidized-bed boiler

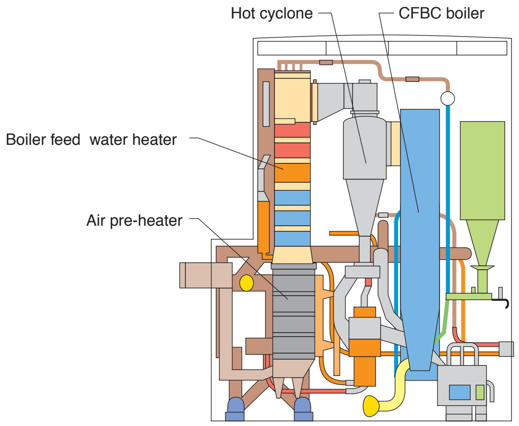


Fig. 2 Schematic drawing of CFBC

Figure 2 provides a rough overview of CFBC. Generally, CFBC consists of a boiler and a high-temperature cyclone. The intra-furnace gas velocity is as high as 4 to 8 m/s. A coarse fluidizing medium and char in the flue gas are collected by the high-temperature cyclone and recycled to the boiler. Recycling maintains the bed height and increases the denitration efficiency. To increase the thermal efficiency, a pre-heater for the fluidizing air and combustion air, and a boiler feed water heater, are installed. Most of the boiler technologies are manufactured overseas, mainly from Foster Wheeler, Lurgi, Steinmuller, ALSTOM, and Babcock & Wilcox.

3. Study site and application field

Photo 1 shows an overview of a CFBC boiler facility. The CFBC gained popularity mainly as a coal-fired boiler. Recently, however, CFBC boilers using RDF and wood-based biomass as the fuel have drawn attention. Typical applications of coal-fired biogas are the Kuraray Co., Ltd.'s Tamashima plant (70 t/hr), Idemitsu Kosan Co., Ltd.'s Chiba oil refinery (300 t/hr), and Ube Industries, Ltd.'s Isa plant (210 t/hr). An example of an RDF-fired boiler is Sanix Inc.'s Tomakomai plant. The biomass fuel is mixed with coal and combusted, thereby decreasing CO_2 emissions.

Photo 1 CFBC appearance

4. Study period

Most of the circulating, atmospheric-pressure fluidized-bed boiler (CFBC) technologies were introduced into Japan from abroad, beginning around 1986.

5. Progress and development results

CFBC technology was introduced from abroad and used in coal-fired boilers. It is used by power producers, iron makers, paper producers, and in other sectors. Plans exist to distribute CFBC technology to China under the Green Aid Plan (GAP).

Outstanding CFBC-related issues include the further investigation of and efforts to reduce the initial costs and to improve the power generation efficiency for boilers using fuels such as RDF, industrial waste, and wood-based biomass.

2A3. Internal Circulating Fluidized-bed Combustion Technology (ICFBC)

Research and development: Japan Coal Energy Center; Ebara Corporation; Idemitsu Kosan Co., Ltd.
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1987-1993

Technology Overview

1. Features

The basic characteristics of ICFBC are described below:

I. Uniform temperature in fluidized-bed, owing to the swirling flow of sand.

II. Easy discharge of non-combustibles, also owing to vigorous movement of sand.

III. Ability to control the temperature of the fluidized-bed by adjusting the heat recovery from the fluidized-bed.

Based on these, ICFBC has the following features:

1) Adoption of various fuels

Similar to CFBC, ICFBC is capable of using not only fossil fuels, such as high-grade coal, oil, and gas, but also low-grade coal, biomass, sludge, waste plastics, and waste tires.

2) Control of bed temperature

Since the overall heat transfer coefficient varies almost linearly with the variations in the air-flow rate in the heat recovery chamber, the quantity of recovered heat is easily regulated through the control of the air-flow rate. In addition, control of the quantity of recovered heat regulates the temperature of the fluidized-bed. Since the control of the recovered heat is performed solely by varying the air-flow rate, adjusting the load is very simple, which is a strong point of ICFBC.

3) Low polluting

NOx and SOx emissions are significantly decreased without special environmental modifications. For the fluidized-bed boiler, desulfurization takes place mainly in the furnace. However, ICFBC does not have a heat transfer tube in the fluidizing section, so the boiler does not cause wear on the heat transfer tube in the bed. Because of this, silica sand can be used as the fluidizing material for ICFBC, instead of soft limestone. As a result, ICFBC needs minimum quantities of limestone as an intrafurnace desulfurization agent. The desulfurization efficiency of ICFBC approaches 90% at a Ca/S molar ratio of around two, though the efficiency depends on the coal grade, the amount of limestone applied, and the temperature of the fluidized bed. Denitration is conducted through a two-stage combustion process: the reducing combustion at the fluidized-bed section, and the oxidizing combustion at the freeboard section. The unburned carbon from the boiler is collected by the high-temperature cyclone installed at the exit of the boiler. The collected, unburned carbon is recycled to the boiler to increase the denitration efficiency.

4) Space-saving, ease of maintenance

Similar to CFBC facilities, ICFBC facilities do not need separate units for desulfurization, denitration, and fine-fuel crushing. Therefore, ICFBC facilities are space saving and easier to maintain because trouble-spots are minimized.

2. Technology overview

Figure 1 shows an overview of ICFBC. The technology uses silica sand as the fluidizing material. The fluidized-bed is divided into the main combustion chamber and the heat recovery chamber by a tilted partition to create a swirling flow inside the main combustion chamber and a circulation flow between the main combustion chamber and the heat recovery chamber. A circulation flow is created to return the unburned char and unreacted limestone from the cyclone at the exit of the boiler to the boiler.

1) The swirling flow in the main combustion chamber is created by dividing the window box in the main combustion chamber into three sections, and by forming a weak fluidized-bed (moving bed) at the center section, introducing a small amount of air while forming strong fluidized-beds at both end-sections and introducing large volumes of air. As a result, the center section of the main combustion chamber forms a slow downward moving bed, and the fluidizing material, which is vigorously blown up from both ends, settles at the center section, and then ascends at both end-sections, thereby creating the swirling flow.

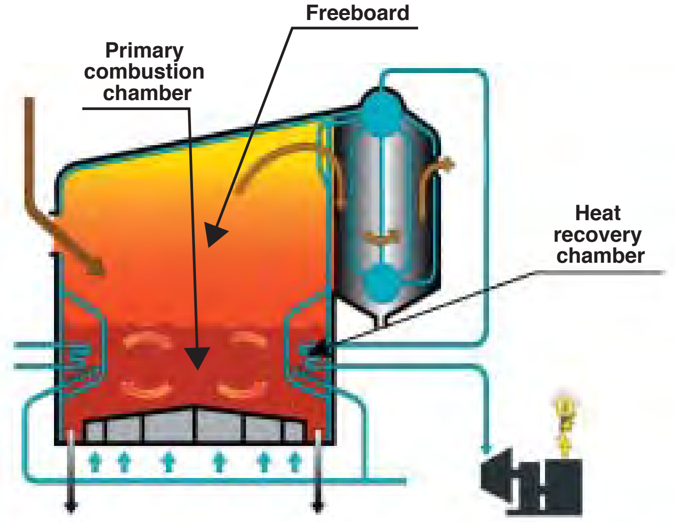


Fig. 1 Overview of ICFBC

2) The circulation flow between the main combustion chamber and the heat recovery chamber is created by the movement described hereafter: A portion of the fluidizing material, which is vigorously blown up at both end-sections in the main combustion chamber, turns the flow direction toward the heat recovery chamber at a position above the tilted partition. The heat recovery chamber forms a weak fluidized-bed (downward moving bed) through the circulation bed air injected from under the chamber. Accordingly, the fluidizing material circulates from the main combustion chamber to the heat recovery chamber, and again to the main combustion chamber from the lower part of the heat recovery chamber. Since the heat recovery chamber is equipped with heat transfer tubes, the circulation flow recovers the thermal energy in the main combustion chamber.

3) The circulation flow from the cyclone at the exit of the boiler passes through the cyclone or other means to collect unburned char, emitted fluidizing material and unreacted limestone, and then returns to the main combustion chamber or the heat recovery chamber, using a screw conveyer, pneumatic conveyer, or other means. The circulation flow is extremely effective in increasing the combustion efficiency, decreasing the generation of NOx, and improving the desulfurization efficiency.

Photo 1 ICFBC site

3. Study sites and application fields

Examples of locations and companies using coal-fired ICFBC include: Chingtao, EBARA CORP. (10 t/hr); Jiangsan in China (35 t/hr); and Nakoso, Nippon Paper Industries Co. (104 t/hr). Examples of locations and companies using ICFBC using industrial waste as the fuel include: Motomachi, Toyota Motor Corp. (70 t/hr); Tochigi, Bridgestone Corp. (27 t/hr); Fuji, Daishowa Paper Mfg. Co., Ltd. (62 t/hr); Amaki, Bridgestone Corp. (7.2 t/hr); and Akita, Tohoku Paper Mfg. Co., Ltd. (61.6 t/hr). In Shizuoka, Chugai Pharmaceutical Co., Ltd. is operating an RDF-fueled ICFBC site (3.7 t/hr).

4. Development period

ICFBC was developed in 1987, and was further developed and validated as a low-polluting, small-scale, and high-efficiency fluidized-bed boiler for multiple coal grades in the "Study of Fluidized-bed Combustion Technology," conducted by the Coal Utilization Technology Promotion Grant project of the Ministry of International Trade and Industry over the course of six years from 1988 to 1993.

5. Progress and development results

Although ICFBC was initially developed to use high calorific value industrial waste, it was improved to use solid fuel with a high calorific value and has been developed as a coal-fired boiler. A boiler plant was constructed in China, a country with abundant coal reserves, in the city of Chingtao, a manufacturing base. Recently in Japan, wood-based biomass has been used as a fuel in some cases. However, a further reduction in up-front investment costs is required to disseminate the technology to Southeast Asia and other areas rich in biomass resources and low-grade coal.

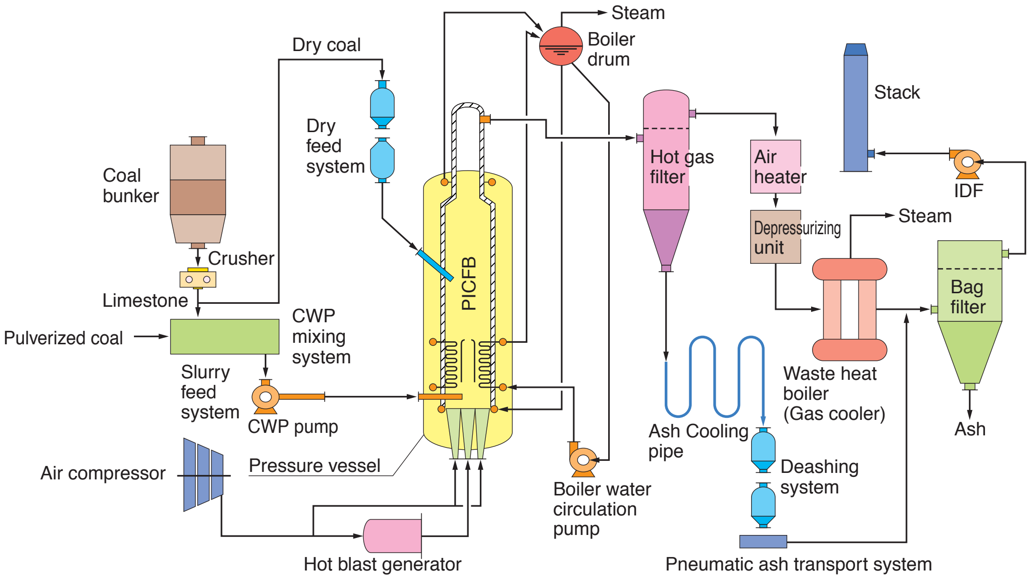


Fig. 2 Flowchart of PICFBC model test plant

2A4. Pressurized Internal Circulating Fluidized-bed Combustion Technology (PICFBC)

Research and development: Japan Coal Energy Center; Ebara Corporation
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1992-1998

Technology Overview

1. Overview

PICFBC's basic technology is the technology of the internal circulating fluidized-bed combustion boiler (ICFBC) described in the preceding section. The PICFBC mounts ICFBC in a pressurized vessel.

2. Features

The pressurized internal circulating fluidized-bed boiler (PICFBC) applies the circulation flow technology of the previously-described ICFBC. Accordingly, the load is controllable without varying the height of the fluidized-bed. In addition, cooling of the combustion gas is avoided because the intra-bed heat transfer tubes are not exposed on the bed during the load controlling action, which minimizes the generation of CO2 and eases the maintaining temperature at the inlet of the gas turbine. Since the wear problems of the heat transfer tube in the bed are decreased, silica sand can be used as the fluidizing material, and the amount of limestone can be minimized to a level necessary for the intra-furnace desulfurization, thus suppressing the generation of ash. Furthermore, the main combustion chamber has no intra-bed heat transfer tube so that the problem of interference of the intra-bed heat transfer tube against the movement of the particles does not occur, which prevents the generation of agglomeration, the solidification of a melted medium.

3. Technology overview

Fig. 1
Schematic drawing of PICFBC

Figure 1 shows a schematic drawing of a PICFBC. The cylindrical pressure vessel contains a cylindrical ICFBC. Similar to ICFBC, silica sand is used as the fluidizing material. The fluidized-bed is divided into the main combustion chamber and the heat recovery chamber by the tilted partition. The swirling flow is created in the main combustion chamber, and the circulation flow is created between the main combustion chamber and the heat recovery chamber.

Figure 2, (p. 27), shows a basic system flowchart of a pilot plant test in Sodegaura plant. The coal feed unit has two lines: the lock hopper system, which feeds lump coal, and the CWP (Coal Water Paste) system, which feeds coal as slurry mixed with water. The flue gas dust is removed by a ceramic high-temperature bag filter. The lock hopper system technology is applied to develop the pressurized two-stage gasification technology.

4. Study sites and application fields

The PICFBC pilot plant test was carried out at a site next to the Idemitsu Kosan Co., Ltd.'s Coal Research Laboratory (Nakasode, Sodegaura City, Chiba). Potential applications include the steam turbine generator, using the generated steam, and the gas turbine generator, using the combustion flue gas. IGCC at coal-fired thermal power plants, therefore, are potential candidates for the technology. Photo 1 shows a PICFB hot model installation of 4 MWth. Photo 2 shows an overview of a pressurized two-stage gasification plant (30 t/d of waste plastics throughput). The pressurized two-stage gasification technology can be utilized to synthesize ammonia from coal, as well as to produce hydrogen for fuel cell power generation. The pressurized two-stage gasification technology has been in operation as a commercial plant (195 t/d of waste plastics throughput) at Showa Denko K.K.'s Kawasaki plant since 2003.

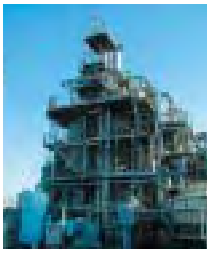


Photo 1
PICFBC facility

Photo 2
Pressurized, two-stage gasification plant

5. Period of development

The ICFBC pilot plant test was carried out from 1992 to 1997, jointly conducted with the Center for Coal Utilization, Japan (now known as JCOAL), as a Coal Utilization Technology Promotion Grant Project of the Ministry of Economy, Trade and Industry (formerly the Ministry of International Trade and Industry). The test operation began in December 1996. The pressurized, two-stage gasification technology was developed jointly with Ube Industries, Ltd. Demonstrative operation of the plant (30 t/d of waste plastics throughput) began in January 2000, and commercial operation commenced in January 2001.

6. Progress and study subjects

As a coal-fired PICFBC, the study progressed to the pilot plant test at Sodegaura. The technology, however, was developed to a pressurized two-stage gasification technology in which a thermal load and a lock hopper system in the pressurized fluidized-bed have been applied. The issues of the pressurized system include the improvement of the reliability of the lock hopper system in the fuel charge line as well as measures to prevent low temperature corrosion.

2A5. Coal Partial Combustor Technology (CPC)

Research and development: Japan Coal Energy Center; Kawasaki Heavy Industries, Ltd.; JFE Steel Corp.; Chubu Electric Power Co., Inc.; and J-POWER
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1978-1986 (9 years)

Technology Overview

1. Background and technology overview

Owing to the abundant reserves and wide distribution of producing countries, the supply of coal is highly stable, and coal is well positioned as an important energy source for the future. However, compared with other fuels, such as oil and gas, coal contains large amounts of ash and nitrogen, which poses many utilization issues, including equipment problems caused by ash, and significant increases in NOx emissions. Furthermore, global warming has become an international concern in recent years, making it an urgent requirement to develop technology to reduce CO_2 emissions, one of the main causes of global warming. Since coal generates a large volume of CO_2 per calorific value, there is a need worldwide to develop technology to use coal in a highly-efficient, environmentally compatible way. A Coal Partial Combustor (CPC) is a furnace where coal and air are injected at high speed into a swirling melting furnace in a tangential direction, thus partially combusting (gasification) the coal under the conditions of a high-temperature, heavy load, and strong reducing atmosphere. After most of the ash in the coal is melted and separated for removal, the produced fuel gas is subjected to secondary combustion. CPC is a technology of coal gasification combustion in a boiler or a gas turbine to utilize coal highly-efficiently and in an environmentally compatible manner. There are two variations of CPC technology: one utilizing atmospheric pressure to produce atmospheric pressure clean gas with low calorific value, and the other under a further pressurized environment to produce highly-efficient power generation in combination with a gas turbine.

2. Atmospheric pressure coal partial combustor technology

Slag-tap boilers aim to reduce the volume and detoxify the ash discharged from the boiler and to use difficult-to-combust coal. They have been constructed and have been operated in a large number of Western countries. The conventional slag-top boiler has the advantages of high combustion efficiency and the recovery of ash as nontoxic molten slag. However, the method has the drawback of significant NOx emissions caused by high-temperature combustion.

Responding to this issue, our technology development focused on the development of a coal partial-combustor system aiming to simultaneously remove the ash from coal and limit NOx emissions. The developed system has the CPC directly mounted to the side wall of the boiler. The combustible gas generated in the CPC is directly injected to the boiler furnace, where the gas is completely combusted with injected air.

As small to medium coal-fired boilers, CPC can significantly reduce NOx emissions while maintaining the compactness of the boiler on a scale similar to that of an-oil fired boiler. It can recover all the coal ash as molten slag. Figure 1 shows a schematic drawing of a atmospheric pressure CPC boiler.

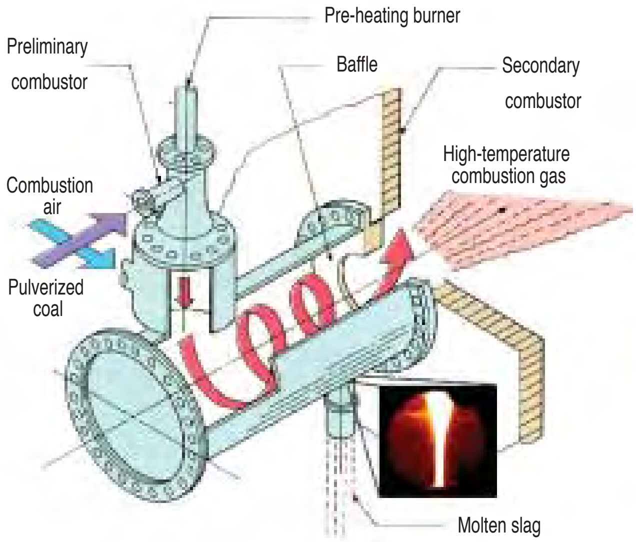


Fig. 1 Schematic drawing of an atmospheric pressure coal partial combustor (CPC) boiler

3. Pressurized coal partial combustor technology

On the basis of the results of the atmospheric pressure CPC development, the development of pressurized CPC technology began, with the objective of developing a high-efficiency power generation system by pressurizing CPC and combining it with a gas turbine.

Figure 2 below shows a basic flow chart of a pressurized CPC pilot plant having 25 t/d of coal gasification capacity (operating at 21% oxygen). The pilot plant ran the coal gas generation test using CPC under a pressure of 20 ata, which can be applied to a gas turbine. The test proved the effectiveness of the pressurized CPC.

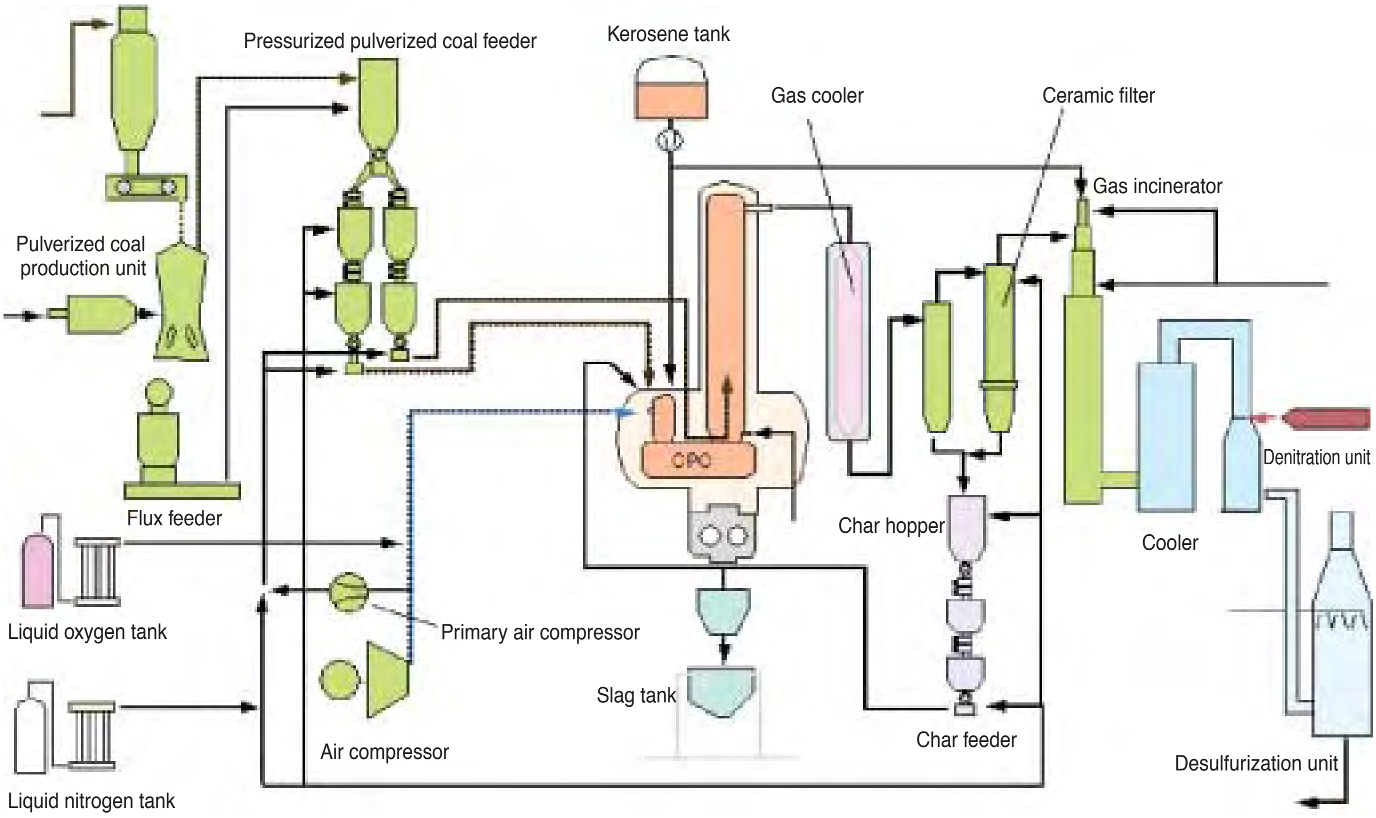


Fig. 2 Basic flow chart of a pressurized CPC pilot plant

4. Issues and feasibility of practical application

Atmospheric pressure CPC technology has already been brought into practical application as a low NOx emission technology in swirling melting furnaces of municipal waste gasification melting furnaces and in very low NOx boilers for heavy oil combustion. Atmospheric pressure CPC technology is also being used in the development of a coal-ash-melting, low NOx boiler. A pilot plant test for the pressurized CPC technology is nearing completion, and the technology is in the research and development stage in the private sector, with the aim of bringing it to practical use. These basic technologies have also been integrated with the development of biomass gasification gas turbine power generation technology.

Photo 1 Pilot plant

2A6. Pressurized Fluidized-bed Combustion Technology (PFBC)

Research and development: Japan Coal Energy Center; and J-POWER
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1989-1999 (11 years)

Technology Overview

1. Background and process overview

(1) The research and development of pressurized fluidized-bed combined power generation technology was conducted at J-POWER's Wakamatsu Coal Utilization Research Center (now known as Wakamatsu Research Institute) using a 71 MWe-PFBC Plant, the first PFBC plant in Japan. The test plant was the first plant in the world to adopt a full-scale ceramic tube filter (CTF) capable of collecting dust from high-temperature, high-pressure gas at a high-performance level. An overview of the process is shown in Figure 1.

(2) Overview of facilities

Plant output 71.0 MWe

Pressurized fluidized-bed combustion boiler (ABB-IHI production)
- Bubbling-type pressurized fluidized-bed, coal water paste (70-75%) injection-type
- Combustion temperature: 860°C
- Combustion air pressure: 1 MPa

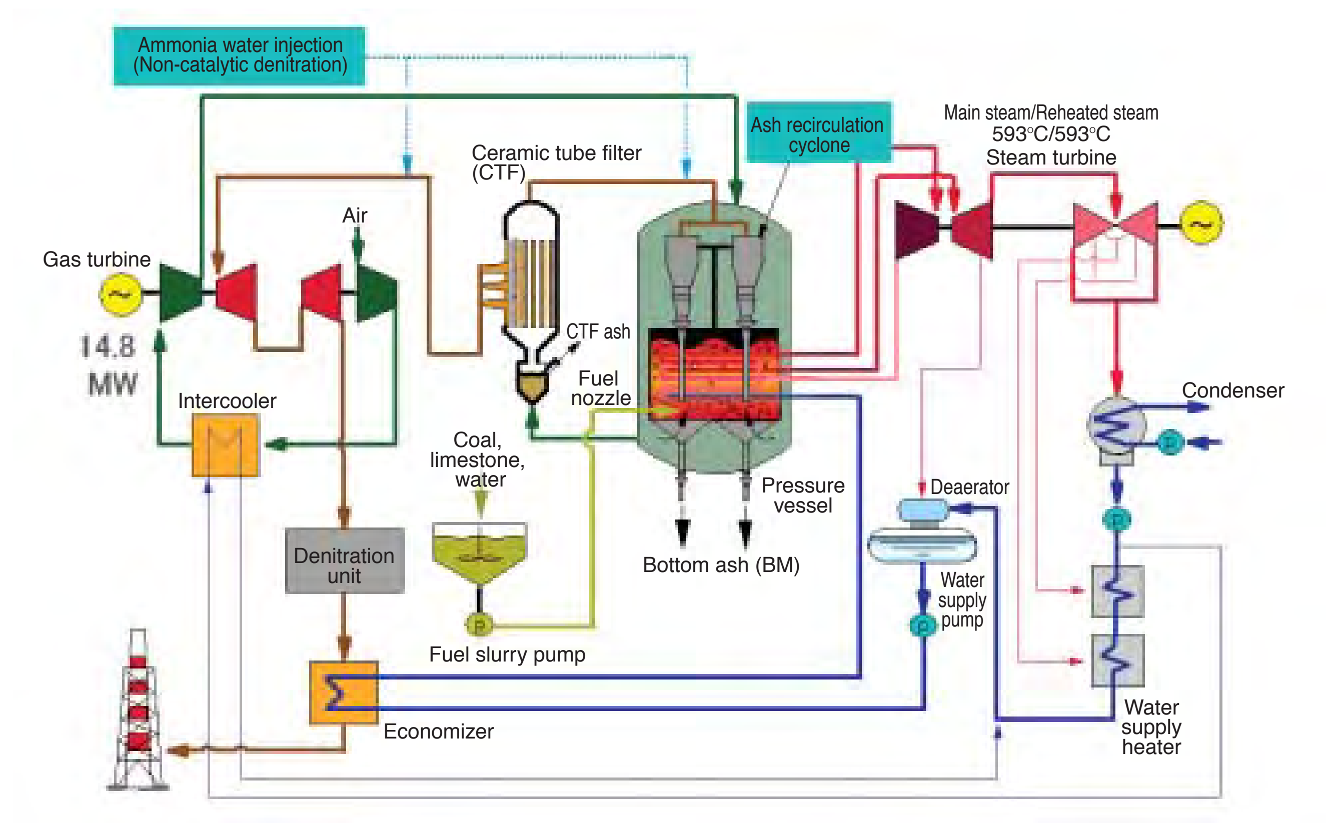


Fig. 1 Flowchart of PFBC process

2. Development objective and technology to be developed

PFBC technology development objectives:

(1) Increase efficiency through combined power generation utilizing pressurized fluidized-bed combustion with a gross efficiency of 43%.

(2) Providing advanced environmental features, including:

SOx reduction through in-bed desulfurization; NOx reduction through low-temperature combustion (approximately 860°C); Dust reduction by CTF; and CO_2 reduction through increased efficiency.

(3) Space-savings through a compact pressurized boiler and the elimination of the desulfurization unit.

Results of PFBC technology development:

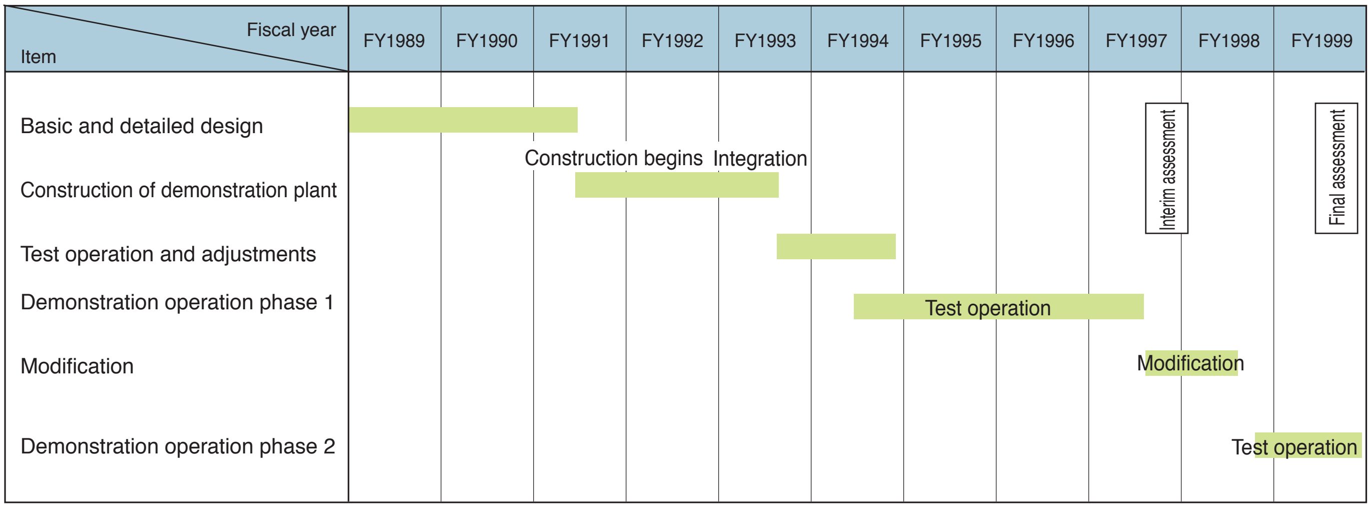
(1) Gross efficiency of 43% was achieved by increasing efficiency through combined power generation utilizing pressurized fluidized-bed combustion.

(2) SOx level of approximately 5 ppm through in-bed desulfurization; NOx level of approximately 100 ppm through low-temperature combustion (approximately 860°C), and dust of less than 1 mg/Nm^3 by CTF.

3. Progress and development results

Detailed design of the facilities began in FY1990 and construction began in April 1992, with equipment installation commencing in October 1992. Test operations began in April 1993, while coal combustion was commenced in September 1993, and 100% load capacity was achieved in January of 1994. The two-stage cyclone system passed inspections before entering operations in September 1994, and the CTF passed inspections before entering operations in December 1994. Phase 1 of the demonstration operation was conducted until December 1997. After that, the plant was modified to adopt the ash-recycling system. Phase 2 of the demonstrative operation was conducted from August 1998 to December 1999. The cumulative operating time of the PFBC system was 16,137 hours, including 10,981 hours in phase 1 and 5,156 hours in phase 2. In phase 2, the system was operated continuously for 1,508 hours. Through the operation, valuable data and findings were made in terms of performance and reliability. Three electric power companies have already applied these results during the construction of commercial facilities.

PFBC development schedule



4. Issues and feasibility of practical application

Due to its environment-friendly characteristics, including SOx emissions of 10ppm or less, NOx emissions of 10 ppm, and dust concentration of 1mg/Nm^3 or less, and also due to the space-savings brought about by the elimination of the desulfurization unit, the PFBC system is highly suitable for urban-operation. These advantages are obtained by: the flexibility to utilize a variety of fuels, such as difficult-to-combust or low-grade materials and waste by utilizing the technology's superior combustion performance; the in-bed desulfurization; the combination of catalytic or non-catalytic denitration; and the high-temperature and high-performance dust collection from the CTF. An outstanding issue is improving the cost-efficiency by fully leveraging these characteristics of the system and by selecting a proper location.

Reference

Yamada et al., "Coal Combustion Power Generation Technology," Bulletin of the Japan Institute of Energy, Vol. 82, No. 11, pp. 822-829, November 2003.

2A7. Advanced Pressurized Fluidized-bed Combustion Technology (A-PFBC)

Research and development: Japan Coal Energy Center; J-POWER; Chubu Electric Power Co., Inc.; and Mitsubishi Heavy Industries, Ltd.
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1996-2002

Technology Overview

1. Overview

The development of high-efficiency power-generation technology utilizing coal is an urgent issue from the perspective of reducing greenhouse gas emissions and conserving resources. Advanced Pressurized Fluidized-bed Combustion (A-PFBC) technology is a further advancement of the Pressurized Fluidized-bed Combustion (PFBC) technology. The development aim is to increase the temperature at the inlet of the gas turbine from approximately 850°C to approximately 1,350°C, and to recover the high-temperature steam, thus attaining more efficient power generation (approximately 46% net efficiency; approximately 40% for existing coal-fired power plants) through combining PFBC technology with the fluidized-bed gasification technology.

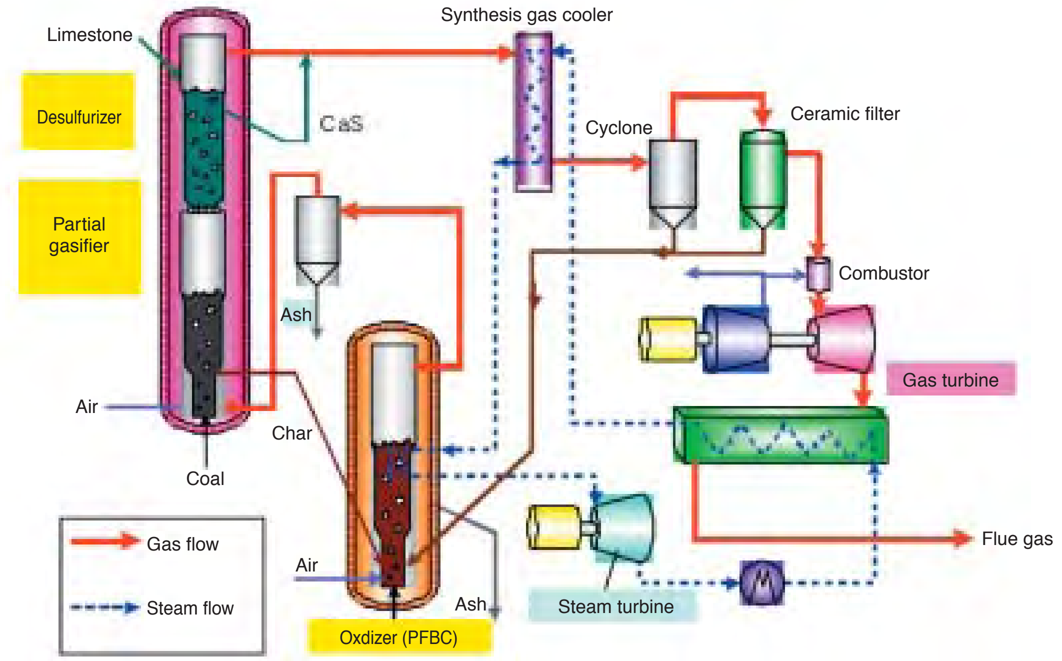


Fig. 1 Flowchart of A-PFBC combined power generation system

2. Development objective and technology to be developed

(1) High-efficiency power generation
Net efficiency: approximately 46%

- Increase of gas turbine inlet temperature (from approximately 850°C to approximately 1,350°C)
- Recovery of high-temperature steam (High-temperature steam recovery at the synthesis gas cooler applying the high-temperature desulfurizer)

(2) Moderation of gasification conditions
Carbon conversion: approximately 85%

- Gasification in the partial gasifier in combination with the oxidizer (perfect oxidizing atmosphere)

(3) Utilization of results of related technologies

- PFBC technology
- Various coal gasification technologies

3. Progress and development results

Aiming for the practical application of the above-described system, the study team installed a small-scale process development unit (Fig. 3) at J-POWER's Wakamatsu Research Institute (Kita Kyushu City). The PDU test operations began in July 2001. By the end of FY2002, the cumulative gasification operation time had reached 1,200 hours, and the continuous gasification operations had reached 190 hours. The PDU test confirmed the successful integration of the three-reactors, which was one of the objectives of the system validation, and the acquired characteristics of each reactor, thus confirming the data necessary for scaling-up.
Further development requires a validation of the total system, combined with a gas turbine in a pilot-scale plant.

(1) Overview of the process development unit (PDU) test
Objectives of the test
For the three-reactor combined system (oxidizer, partial gasifier, and desulfurizer), (Fig. 2), data is acquired on the
reaction characteristics and operation characteristics, and the validation of the process is carried out in order to acquire information necessary for scaling-up the system.

- Validation of the three-reactor link process
- Confirmation of the performance of the individual systems (oxidation, gasification, desulfurization, etc.)
- Confirmation of basic operability
- Information on various characteristics, acquisition of data for scaling-up, etc.

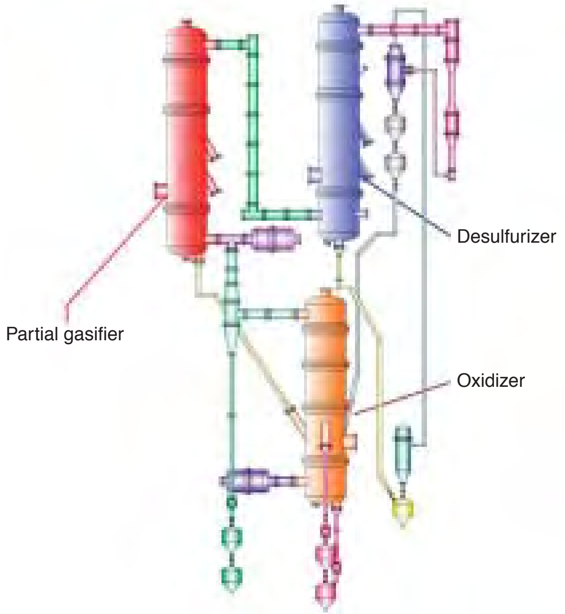
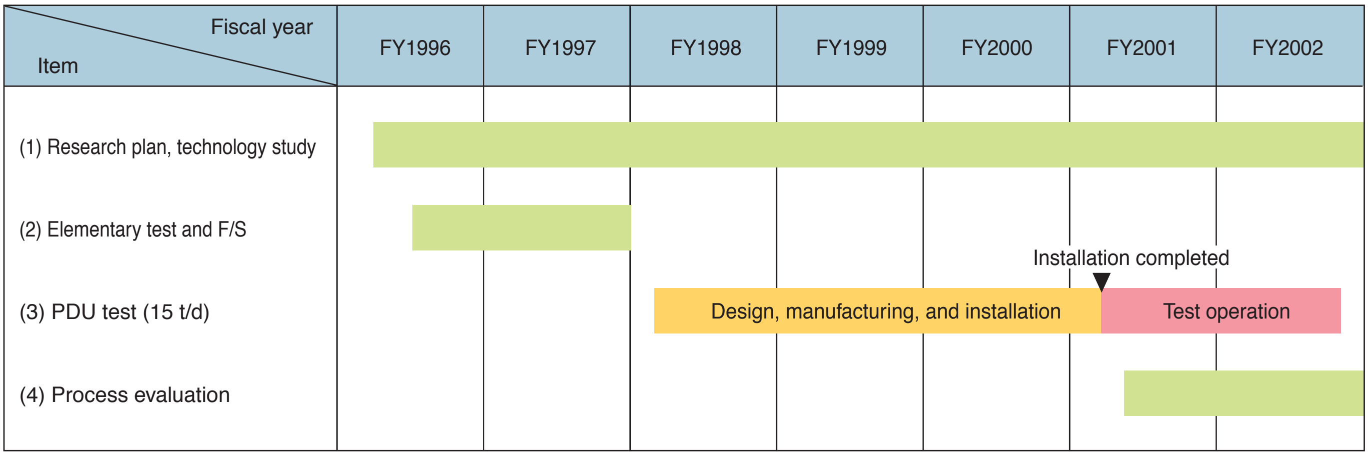


Fig. 2 PDU: Schematic layout of the three reactors

Fig. 3 PDU overview

A-PFBC development schedule



Item \ Fiscal year	FY1996	FY1997	FY1998	FY1999	FY2000	FY2001	FY2002
(1) Research plan, technology study	🟩	🟩	🟩	🟩	🟩	🟩	🟩
(2) Elementary test and F/S	🟩	🟩					
(3) PDU test (15 t/d)			Design, manufacturing, and installation	Design, manufacturing, and installation	Design, manufacturing, and installation	Installation completed Test operation	Test operation
(4) Process evaluation						🟩	🟩

Reference

Preprint for the 13th Coal Utilization Technology Congress, "A-PFBC"; sponsored by the Center for Coal Utilization (now known as JCOAL).

2B1. Hydrogen-from-Coal Process (HYCOL)

Research and development: HYCOL Association [Idemitsu Kosan Co., Ltd. ; Osaka Gas Co., Ltd.; J-POWER; Tokyo Gas Co., Ltd.; Toho Gas Co., Ltd.; Nikko Kyoseki Co., Ltd.; The Japan Steel Works, Ltd.; Hitachi Ltd.; and Mitsui Coal Liquefaction Co., Ltd.]
Project type: NEDO entrusted project

Technology Overview

1. Background and process overview

The Hydrogen-from-Coal Process (HYCOL) is a gasification technology utilizing an entrained bed, in which pulverized coal is gasified with oxygen under high temperatures and high pressure. Through the gasifier, medium calorific gas, rich in hydrogen and carbon monoxide, is obtained. The technology is called the "HYCOL process." Through the shift reaction, the gas yields carbon monoxide and converts steam to carbon dioxide and hydrogen. After separating the carbon dioxide, the gas is purified to become high-purity hydrogen.

Hydrogen is used in oil refineries and in the chemical industry, as well as in the coal liquefaction process. On the other hand, the gas containing carbon monoxide is expected to be used widely as a raw material for synthetic chemical products, as a fuel for fuel cells, and as a fuel in various industries.

The HYCOL process has the following features:

(1) The process uses a dry-feed, one-chamber, two-stage swirling-entrained-bed gasification furnace. Pulverized coal, pressurized in a lock hopper, is fed, to the gasification furnace via burners in a swirling mode. Four burners are utilized in each stage. The oxygen feed and the gasification rate at the upper stage and lower stage are separately controlled. Throughout the operation, high thermal efficiency is attained, and heavy load gasification is performed.

(2) Slag self-coating technology for the water-cooled tubes was applied. This technology prolongs the life of the tubes and improves the reliability of the gasifier.

(3) A swirling gas flow distributor was developed and adopted as a technology to easily and uniformly distribute coal to multiple burners.

(4) Ash in coal is melted in the gasification furnace. The melted ash is discharged through the slag hole located in the furnace’s hearth. As a result of the swirling gas flow, a high temperature is maintained at the slag hole, ensuring a smooth flow of slag.

(5) The unreacted char discharged along with gas from the gasification furnace is separated by a cyclone or other such device to recycle the material to the gasification furnace in a high-temperature, high-pressure state, thus ensuring a complete reaction.

(6) Ash in the coal is recovered as slag, which does not elute toxic components. Combined with the advantage of an easy recovery of the sulfur and nitrogen components, in the form of H_2S and NH_3, respectively, the ash recovery also significantly contributes to a reduction in the environmental burden.

Coal that has a lower fuel ratio (fixed carbon to volatile matter) is more easily gasified.

2. Progress and development results

The HYCOL association (made up of the nine above-listed private companies) carried out the research and development of the pilot plant, under entrustment from NEDO. Five private companies (Hitachi Ltd., Babcock-Hitachi K.K., Asahi Glass Co., Ltd., Shinagawa Refractories Co., Ltd., and NGK Spark Plug Co., Ltd.) carried out the basic study on the structure of the furnace and on the materials, also under entrustment from NEDO.

For establishing the process, a pilot plant was constructed at Sodegaura, Chiba. The operational study of the pilot plant was conducted from 1991 to 1994. The performance target was achieved, and the world’s most advanced gasification furnace technology was established.

3. Issues and feasibility of practical application

The development of a coal gasification fuel cell system (IGFC) for power generation utilizing HYCOL technology began in 1995, (EAGLE Project).

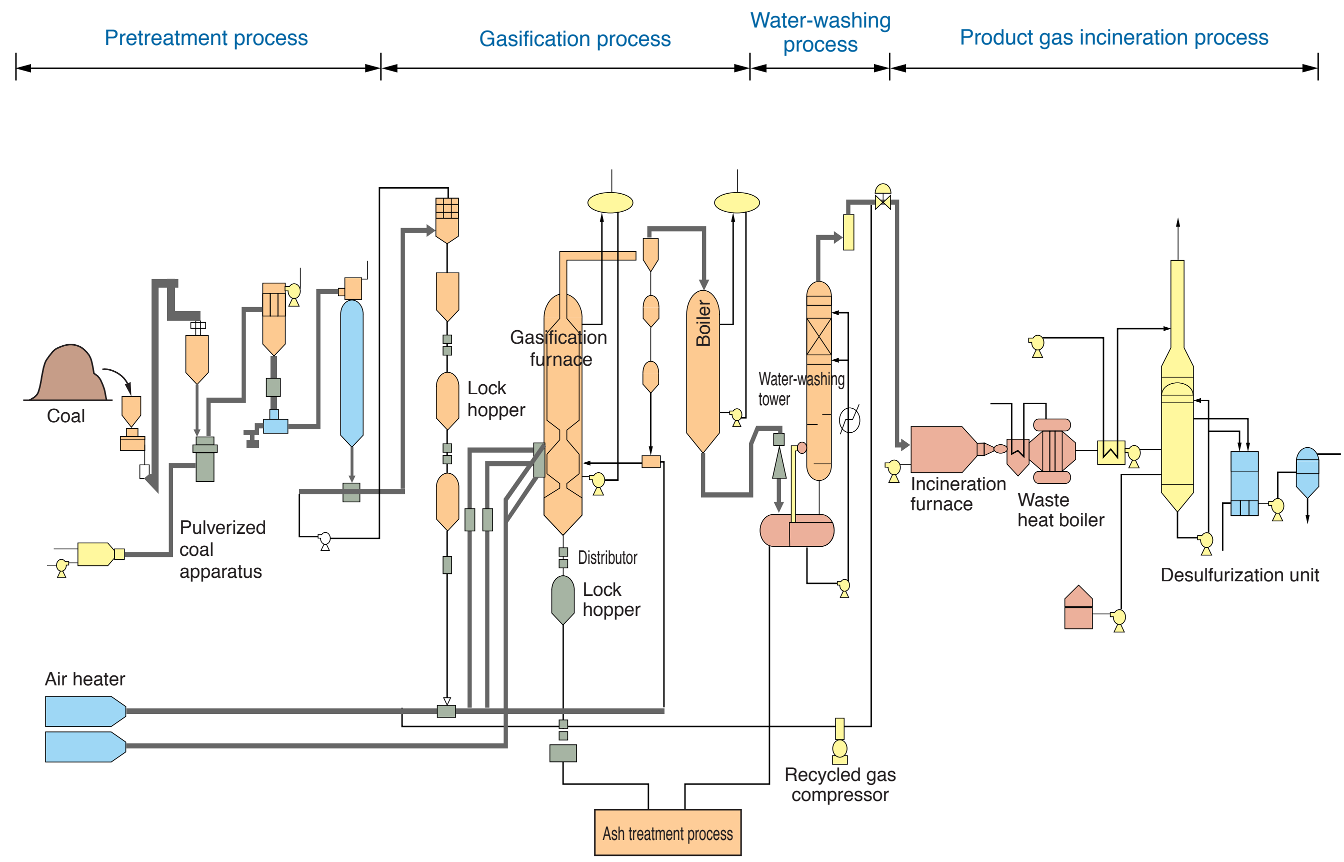


Fig. 1 Process flowchart of pilot plant

Pilot plant: Specifications and target performance

Coal throughput	Max. 50 tons/day
Gasification agent	Oxygen
Gasification pressure	30 kg/cm^2(G)
Gasification temperature	1,500-1,800°C
O_2/Coal	0.8-0.9 (weight ratio)
Produced gas volume	Approximately 91 kNm^3/day
Gas composition (design)	CO 61%
	H_2 31%
	CO_2 3%
Carbon conversion	98% or greater
Cold gas efficiency	78% or greater

2B2. Integrated Coal Gasification Combined Cycle (IGCC)

Research and development: Clean Coal Power R&D Co., Ltd.
(Until 2000, the study had been conducted as a joint activity of power companies led by Tokyo Electric Power Co., Inc.)
Project type: Grant for "Demonstration of Integrated Coal Gasification Combined Cycle Power Generation," the Agency of Natural Resources and Energy of the Ministry of Economy, Trade and Industry
Period: 1999-2009

Technology Overview

1. Overview and objective of IGCC demonstration test

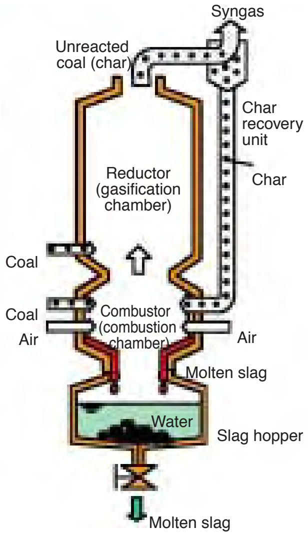


Fig. 1 Nakoso PP-type gasifier

Integrated Coal Gasification Combined Cycle (IGCC) is a high-efficiency power generation technology which gasifies coal to be used as the fuel for gas turbines. Japanese power companies promoted the research and development of IGCC technology, applying a Nakoso pilot plant (PP)-type gasifier[1,2] as the core technology[3]. The PP-type gasifier utilizes dry-coal-fed, oxygen-enriched air-blown, pressurized two-stage entrained beds, as shown in Figure 1. This is expected to provide higher efficiency than preceding gasifiers from abroad. On the basis of the feasibility study results, an IGCC demonstration test project was started with the aim of validating IGCC's reliability, operability, maintainability, and profitability, and to confirm the feasibility of a coal-fired IGCC commercial plant.

Compared with conventional pulverized coal-fired power plants, IGCC has many advantages, such as:

1. Improved power generation efficiency: Compared with conventional pulverized coal-fired power plants, IGCC can increase power generation efficiency by approximately 20% for commercial plants.
2. Lower environmental burden: Owing to the increase in power generation efficiency, the emissions of SOx, NOx, and dust per generated power unit are lower. In addition, CO_2 emissions are reduced to the level of the heavy-oil-fired power generation process.
3. Flexibility to use different grades of coal: IGCC can use coal with low ash melting points, which is difficult to use in conventional pulverized coal-fired power plants. As a result, IGCC broadens the variety of coal grades that can be used in coal-fired power plants.
4. Increase in fields that can utilize the ash: Since IGCC discharges coal ash in the form of glassy molten slag, the ash is expected to be effectively used as component for civil engineering work.
5. Reduction of water consumption: Since the generated gas is desulfurized directly, IGCC does not need a flue gas desulfurization unit, which consumes large amounts of water. Accordingly, IGCC uses significantly less water than conventional pulverized coal-fired power plants.

2. Specifications and objective of IGCC demonstration plant

Figure 2 shows the process flow of the IGCC demonstration plant. Table 1 lists the main specifications and target values. Figure 3 is a conceptional drawing of the IGCC demonstration plant. The scale of the plant (250 MW, 1700 t/d of coal feed) is about one-half of a commercial plant. The gasifier is of the Nakoso PP-type. A wet gas clean up system with MDEA has been adopted. The gas turbine is a 1200°C-class gas turbine, with a corresponding output of 250 MW.

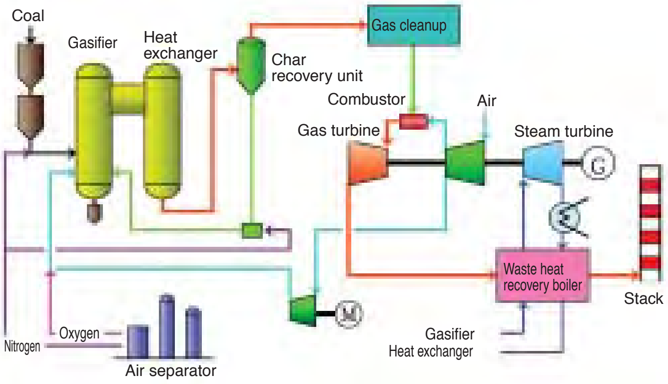


Fig. 2 Process flow of the IGCC demonstration plant

Table 1 Main specifications and target values of IGCC demonstration plant

Output	250 MW class	
Coal feed rate	Approximately 1,700 t/d	
Type	Gasifier	Dry-coal-fed, air-blown, Pressurized, two-stage entrained beds
	Gas cleanup	Wet gas cleanup (MDEA) + gypsum recovery
	Gas turbine	1200°C-class
Target thermal efficiency (LHV)	Gross efficiency	48%
	Net efficiency	42%
Environmental characteristics (target values)	SOx emission concentration	8 ppm (O_2 conversion: 16%)
	NOx emission concentration	5 ppm (O_2 conversion: 16%)
	Dust emission concentration	4 mg/Nm^3 (O_2 conversion: 16%)

3. Organization for executing the IGCC demonstration test

The IGCC demonstrative test is being conducted by Clean Coal Power R&D Co., Ltd. (CCP R&D Co., Ltd.), which was established by nine power companies and J-POWER. The Ministry of Economy, Trade and Industry is subsidizing 30% of the project costs, and 70% of the costs are being borne by a total of eleven entities: nine power companies, J-POWER and the Central Research Institute of Electric Power Industry (Fig. 4).

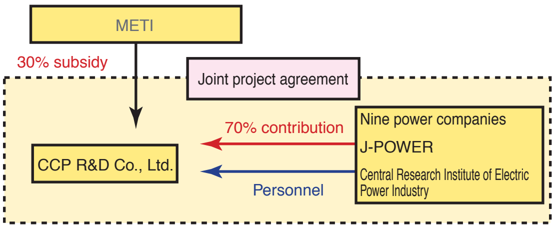


Fig. 4 Scheme of demonstration project

Fig. 3 Conceptional drawing of the IGCC demonstration plant

4. Timetable and progress

Table 2 shows the schedule of the demonstration project. The demonstration plant has been under construction since March 2006. A three-year test operation of the plant is scheduled to begin in the second half of FY2007.

Table 2 IGCC demonstration project timetable

Fiscal year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Preliminary validation test	■	■	■	■							
Design of demonstration plant			■	■	■	■					
Environmental assessment			■	■	■	■					
Construction of demonstration plant						■	■	■	■		
Plant operation and demonstration test									■	■	■

5. Activities to date

The pilot plant test (200 t/d of coal feed), which is a preliminary stage of the demonstration test, was carried out from 1986 to 1996 at Joban Joint Power Co., Ltd.'s Nakoso power plant in Iwaki City, Fukushima, (Fig. 5). The pilot plant test was conducted jointly by nine power companies, plus J-POWER and the Central Research Institute of Electric Power Industry, as an entrusted project of NEDO. A pilot plant test of 4,770 hours, including 789 hours of continuous operation, proved the practical applicability of the IGCC technology[3]. Based on the success of the pilot plant test, a demonstration test introduced an optimum system, which was selected following a feasibility study conducted by NEDO. After conducting a variety of surveys, Joban Joint Power Co., Ltd.'s Nakoso power plant was again selected as the site for the demonstration test, which is being conducted at the same site of the pilot plant.

Fig. 5 Site for demonstration test. (Iwaki City, Fukushima)

References

1) Shozo Kaneko et al., "250MW AIR BLOWN IGCC DEMONSTRATION PLANT PROJECT,"Proceedings of the ICOPE-03, pp. 163-167, 2003.
2) Christopher Higman, Maarten van der Burgt, "Gasification," pp. 126-128, 2003.
3) Narimitsu Araki and Yoshiharu Hanai: Bulletin of Japan Energy, 75-9, pp. 839-850, 1996.

2B3. Multi-purpose Coal Gasification Technology Development (EAGLE)

Research and development: New Energy and Industrial Technology Development Organization; J-POWER; Japan Coal Energy Center; and Babcock Hitachi K.K.
Project type: Coal Production and Utilization Technology Promotion Grant; and Grant for the Development of Advanced Technology for Generation of Fuel Gas for Fuel Cell Development
Period: 1995-2006 (12 years)

Technology Overview

1. Summary of technology

The purpose of EAGLE (Multi-purpose Coal Gasification Technology Development) is to reduce the environmental burden, particularly global warming gas emissions. The EAGLE project aims to establish a coal gasification system utilizing the most advanced oxygen-blown, single-chamber, two-stage swirling flow gasifier that allows the highly-efficient production of synthetic gas ($CO+H_2$), and which can be widely used as a raw material for chemicals, hydrogen production, synthetic liquid fuel, electric power generation and other purposes.

This gasifier, combined with gas turbines, steam turbines, and fuel cells, will provide an integrated coal gasification fuel cell combined-cycle system (IGFC) that can be expected to reduce CO_2 emissions by up to 30% relative to existing thermal power plants.

2. Development targets and technology to be developed

The EAGLE project's development targets are shown in Table 1. When utilizing coal-gasified gas for fuel cell power generation or the production of synthetic fuel, hydrogen, or chemical fertilizers, sulfur compounds and other impurities contained in the gas may contaminate the fuel cells and the reactor catalyst, thereby degrading their performance. The EAGLE project, therefore, sets targets to meet the purity levels required by fuel cells and catalysts. Since there have been few reports published on the matter, particularly on the effects of fuel cell contaminating materials (including halogens), the project set target levels with reference to reports by the U.S. Department of Energy (DOE), the MCFC Association of Japan, and other organizations.

Table 1 Development targets

Item	Development target
Coal gasification performance	Carbon conversion rate: 98% or higher Cold gas efficiency: 78% or higher Gas calorific value (higher): 10,000 kJ/m^{3}N or higher
Gas purification performance	Sulfur compounds: 1 ppm or less Halogen compounds: 1 ppm or less Ammonia: 1 ppm or less Dust: 1 mg/m^{3}N
Miscellaneous	Continuous operation: 1,000 hr or longer Acquisition of gasification data for 5 or more coal types Acquisition of scale-up data

3. Pilot test plant

In this project, a pilot test plant with a coal processing capacity of 150 tons/day was built on the premises of the J-POWER's Wakamatsu Research Institute. Operational testing is now underway. Figure 1 shows a flowchart of the pilot test plant and Table 2 provides the specifications of the major systems. The test plant consists of the following systems: coal pretreatment, coal gasification, air separation, gas purification, effluent treatment, and produced gas combustion, as well as a gas turbine.

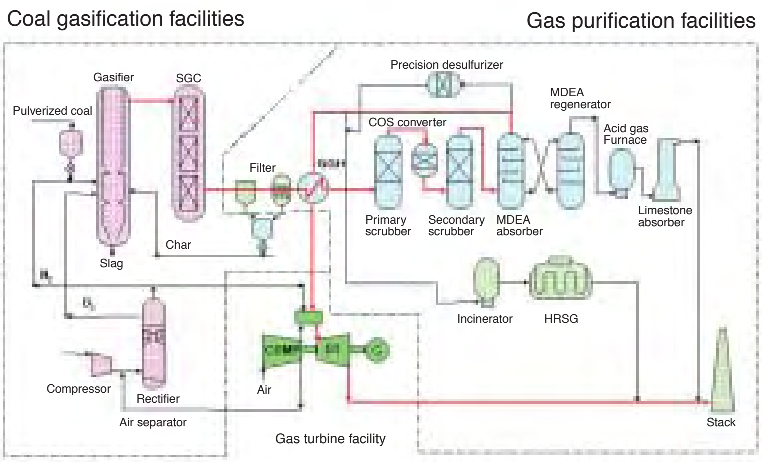


Fig. 1 Flowchart of EAGLE 150 t/d pilot plant

Table 2 Specifications of major systems

Item	Specifications
Coal gasifier	Oxygen-blown, single-chamber, two-stage swirling-flow entrained bed gasifier
Coal processing capacity	150t/d (6.3t/hr)
Gasification temperature	1,200-1,600℃
Gasification pressure	2.5MPa
Gas refinery	Wet chemical absorption type
Absorbing solution	Methyl diethanolamine (MDEA)
Processing capacity	Approx. 14,800 m^{3}N/h
Sulfur recovery unit	Wet limestone-gypsum method
Air separation system	Pressurized cryogenic separation type
Air pressure	1.09MPa
Air processing capacity	Approx. 27,500m^{3}N/hr
Oxygen production	Approx. 4.600m^{3}N/hr
Oxygen purity	95%
Gas turbine	Open simple-cycle, single-shaft type
Output	8,000kW

4. Timetable and progress

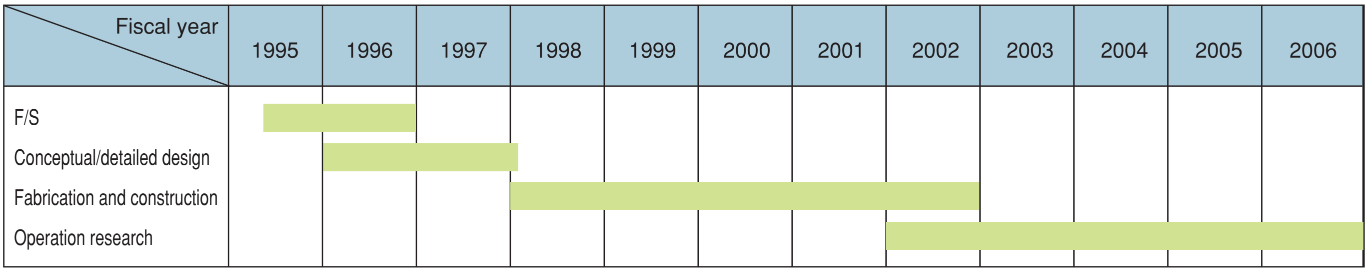
This project is being promoted by a joint team from the New Energy and Industrial Technology Development Organization (NEDO) and the J-POWER. The pilot plant (150 t/d) was constructed on the premises of J-POWER's Wakamatsu Research Institute (Photo 1), and operational testing is now underway.

Table 3 Achievement of research targets

		Final target	Achievements
Coal gasification performance	Gas electric power generation	10,000 kJ/m^{3}N or higher	10,100 kJ/m^{3}N or higher
	Carbon conversion rate	98% or higher	99% or higher
	Cold gas efficiency	78% or higher	78% or higher
Gas purification performance	Sulfur compounds	1 ppm or less	N.D. (<1 ppm or less)
	Ammonia	1 ppm or less	1 ppm[1]
	Halogen compounds	1 ppm or less	1 ppm or less
	Dust	1 mg/m^{3}N	1 mg/m^{3}N or less[2]

Notes: Coal processing capacity of 150 t/d verified
1: at the outlet of the absorber, 2: at the outlet of the second scrubber

EAGLE development timetable



5. Future plans

Major future developments are planned for the project, including support for using multiple grades of coal, acquisition of scale-up data, technological enhancements for improved cost-efficiency, as well as system verification. With a view to achieving the development targets ahead of schedule, these challenges have already been addressed. EAGLE technology can be effectively used in integrated coal gasification combined cycle (IGCC) power generation systems, which combine gas turbine generation systems and steam turbine generation systems, or in an integrated coal gasification fuel cell combined-cycle system (IGFC). This may be the ultimate triple-combined-cycle based on combining IGCC with fuel cells. IGFC is expected to dramatically improve generation efficiency relative to conventional pulverized coal-fired power generation systems, and is the ultimate power generation system, with power generation efficiency exceeding 55%. EAGLE plants using oxygen-blown coal gasifiers produce coal-gasified gas with a substantially lower proportion of non-CO and H_2 gas components (i.e., N_2 and other gases). Utilization of this gas allows the efficient production of liquid fuels or chemical feedstocks.

In the U.S., there is a proposed project to combine a hydrogen gas turbine generation system or a fuel cell power generation system that uses coal-derived hydrogen with a CO_2 separation, collection and segregation system. EAGLE technology is not only expected to meet the future demands of a hydrogen society, but is also expected to meet the demands of today.

Photo 1 Pilot test facilities

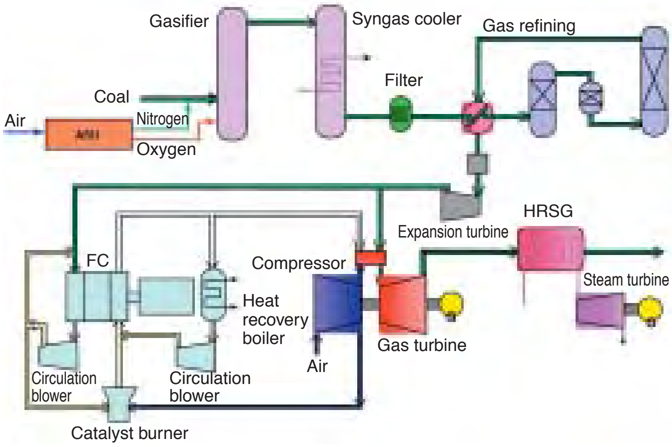


Fig. 2 IGFC system

Reference

1) Masao Sotooka: Coal Gasification Technology (II) — Multi-purpose (Fuel-cell) Coal Gasification Technology Development (EAGLE), The Japan Institute of Energy, Vol.82, No. 11, pp. 836-840, November 2003.

2B4. Integrated Coal Gasification Fuel Cell Combined Cycle Electric Power Generating Technology (IGFC)

Technology Overview

1. IGFC process flow

The integrated coal gasification fuel cell combined cycle (IGFC) gasifies coal for use in triple combined power generation, which combines three different types of generation systems: fuel cells, gas turbines and steam turbines. This high-efficiency power generation technology is expected to provide power generation efficiency of 55% or higher, if successfully developed, and to reduce CO_2 emissions by approximately 30% from the level of existing pulverized coal-fired power generation systems. IGFC is expected to become a coal-fired power generation technology of the future, although there are still many challenges to be overcome for commercialization, including the development of inexpensive high-efficiency fuel cells (Fig. 1).

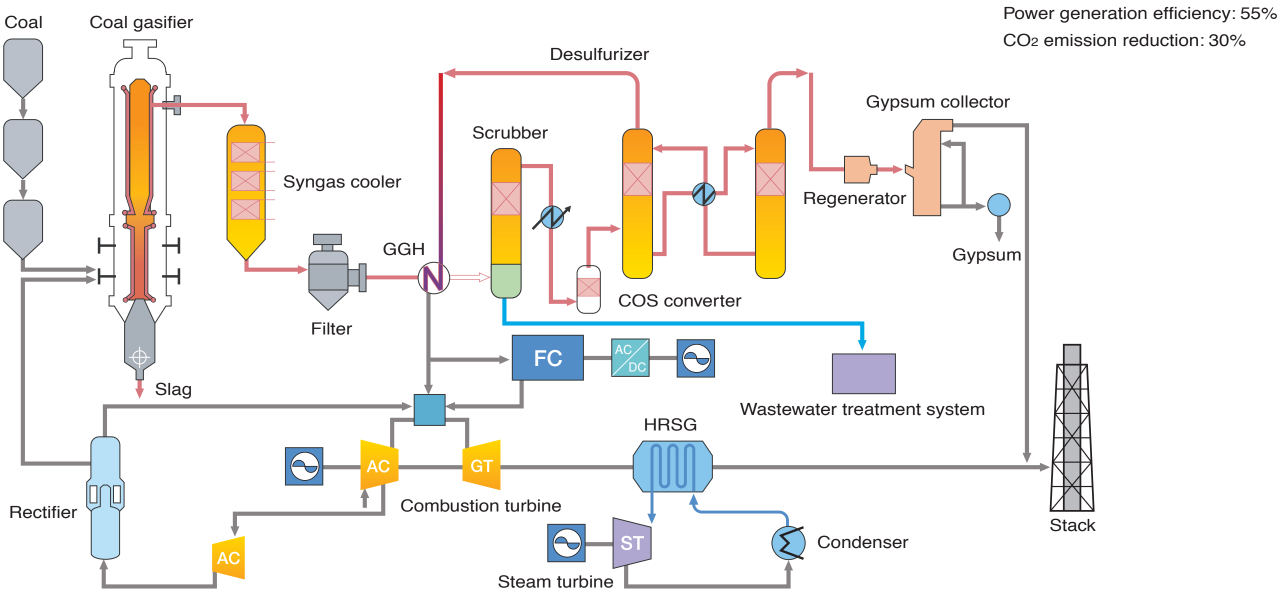


Fig. 1 IGFC process flowchart

2. Types and features of fuel cells

Fuel cells employ the electrochemical reaction between hydrogen and oxygen to directly generate power. With their high-efficiency and excellent environmental features, fuel cells are now in the limelight. They can be classified by electrolyte material into phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and solid polymer electrolyte fuel cells (PEFC).

Type	Phosphoric acid (PAFC)	Molten carbonate (MCFC)	Solid oxide (SOFC)	Solid polymer electrolyte (PEFC)
Electrolyte	Phosphoric acid aqueous solution	Li/Na carbonate	Stabilized zirconia	Solid polymer membrane
Ionic conductor	H^+	CO_3^{2-}	O^{2-}	H^+
Operating temperature	Approx. 200°C	Approx. 650 to 700°C	900 to 1000°C	70 to 90°C
Generation efficiency (HHV)	35% to 42%	45% to 60%	45% to 65%	30% to 40%
Raw materials and fuels	Natural gas, methanol, naphtha	Natural gas, methanol, naphtha, coal	Natural gas, methanol, naphtha, coal	Natural gas, methanol, naphtha
Application	Co-generation and distributed generation	Co-generation and distributed generation, substitute for thermal power generation	Co-generation and distributed generation, substitute for thermal power generation	Co-generation and portable power supply, automobiles

Among the fuel cells above, MCFC and SOFC operate at high temperatures and are expected to be highly-efficient technologies for next-generation large-scale power plants due to the following features: (1) they can be used in combination with gas turbines, and (2) they can accept coal gas.

SOFC produce power through an electrochemical reaction between hydrogen, which has been derived from gasified fuel, and oxygen in the air. This mechanism is the reverse process of the electrolysis of water.

The traditional power generation system burns fuel to generate heat and converts the heat into electrical energy. Unlike this system, fuel cells derive electrical energy directly with lower energy losses and higher generation efficiency.

SOFC, consisting of ion-conducting ceramics, generate heat at temperatures as high as 900°C to 1,000°C during the chemical reaction. Combined with gas turbine generation, SOFC can provide higher generation efficiency than other types of fuel cells. Besides coal-gasified gas, LNG, methanol or biogas can also be used as fuel.

2B5. Next-generation, High-efficiency Integrated Coal Gasification Electric Power Generating Process (A-IGCC/A-IGFC)

Technology Overview

1. Advanced IGCC/IGFC with exergy recovery technology

The integrated coal gasification combined cycle (IGCC) power generation system under development in Japan provides a generation efficiency of 48% for dry gas cleaning. Also, the integrated coal gasification fuel cell combined cycle (IGFC) provides 55%. These efficiency levels are 7% to 8% lower than that of natural gas-fired IGCC/IGFC. An important challenge for Japan is to develop technologies to more efficiently utilize coal, an energy source that can be stably supplied.

Unlike the existing IGCC/IGFC system that integrates partial oxidation gasifiers, fuel cells, and gas and steam turbines using a cascade method of energy utilization, the A-IGCC/A-IGFC (Advanced IGCC/IGFC) system directs recycled heat from gas turbines or fuel cells back into steam reforming gasifiers that employ endothermic reactions. This next-generation exergy recovery-type IGCC/IGFC being studied. With exergy recovery, the A-IGCC, using 1700°C gas turbines, is expected to provide a generation efficiency of 57% and the A-IGFC, employing fuel cells, is expected to provide a generation efficiency as high as 65%. Thus, this technology is expected to have the potential to bring about a dramatic increase in system efficiency, contributing, in the future, to the provision of energy resources and a reduction in CO_2 emissions.

Table 1 Comparison between existing IGCC and A-IGCC

	Existing IGCC/IGFC	A-IGCC/IGFC
System combination	Cascade method	Exergy recovery
Gasification	High-temperature partial oxidation (1100 to 1500°C)	Steam reforming (700 to 1000°C)
Gasifiers	Entrained flow	Multi-loop high density CFB
Generation efficiency	46 to 48% (55%)	53 to 57% (65%)

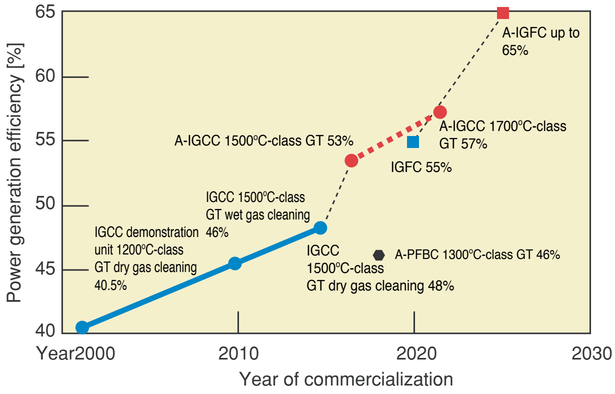


Fig. 1 Projection of A-IGCC/IGFC efficiency

2. Overview of A-IGFC

Figure 2 is a schematic drawing of the basic A-IGFC processes. The existing IGFC, which uses energy in a cascade method, integrates a gasifier, fuel cells, gas turbines and a steam turbine into a cascade-type system. Hydrogen-rich gas produced in the gasifier is purified and then sent to the fuel cell unit. Part of the fuel that has not been used in the fuel cell unit is transferred to the gas turbines for power generation. Since this process provides only a low fuel utilization rate, the inlet temperature of the gas turbines is around 1100°C and the power generation efficiency is not more than 55%. This is a result of the cold gas efficiency of coal, which is as low as approximately 80%. On the other hand, the exergy-recovering IGFC reuses the high-temperature heat generated by the fuel cells in the gasifier for steam reforming gasification by making use of an endothermic reaction. A-IGFC, using exergy recovery technology, can be expected to substantially improve the generation efficiency. Recovering waste heat from the fuel cells with low exergy loss and reusing the heat for steam reforming gasification that relies on an endothermic reaction will greatly enhance the cold gas efficiency and substantially reduce the exergy losses due to combustion.

A-IGFC efficiency: 64.5% (60% plus approximately 5% loss for internal use)
Calculation with SOFC fuel utilization rate of 75% and efficiency of 40%

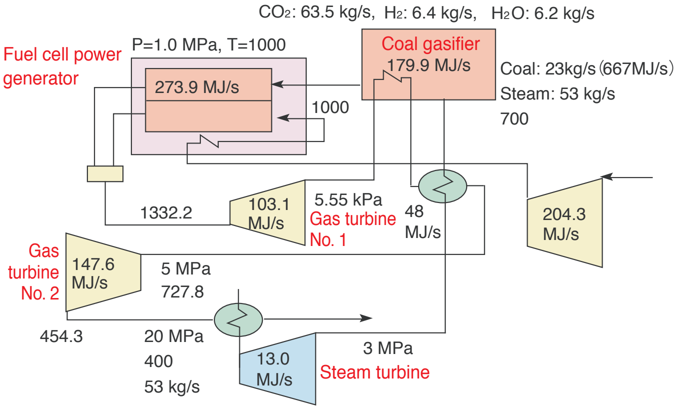


Fig. 2 Schematic drawing of basic A-IGFC processes

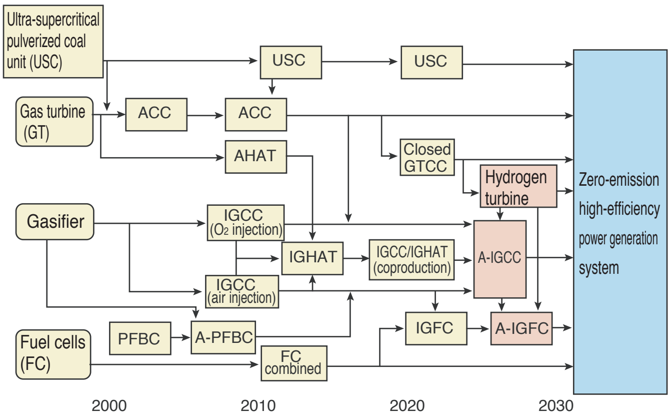


Fig. 3 High-efficiency power generation technology development

3A1. Formed Coke Process (FCP)

Research and development: Japan Coal Energy Center; and Japan Iron and Steel Federation
Period: 1978-1986 (9 years)

Technology Overview

1. Overview

The formed coke process (FCP) utilizes noncaking coal as the main raw material. Next, a binder is used to allow the coal to be shaped, and then it is carbonized in formed shapes in a vertical furnace to obtain coke.

2. Features

A series of steps are employed in FCP, including raw material processing, shaping, carbonizing the formed coal, and cooling the carbonized coke. In particular, the carbonizing and cooling steps are conducted in a vertical furnace within an enclosed system, providing many superior features in terms of work environment, work productivity, ease of system starts and stops. Relative to conventional chamber ovens, FCP systems are compact, meaning less installation space is required.

3. Results of study

1. Production of formed coke from 100% noncaking coal

The pilot plant was normally operated with a blend of 70% noncaking coal and 30% caking coal; however, 100% noncaking coal operation was also attained.

2. Establishing stable operating technology and engineering technology

The pilot plant was operated for an extended period at the facility capacity of 200 tons/day. Production of 300 tons/day, or 1.5 times the designed capacity, was also achieved. Regarding the unit requirement of heat, 320 Mcal/t-formed coal was achieved.

3. Extended period of operation and continuous use of 20% formed coke in large blast furnace

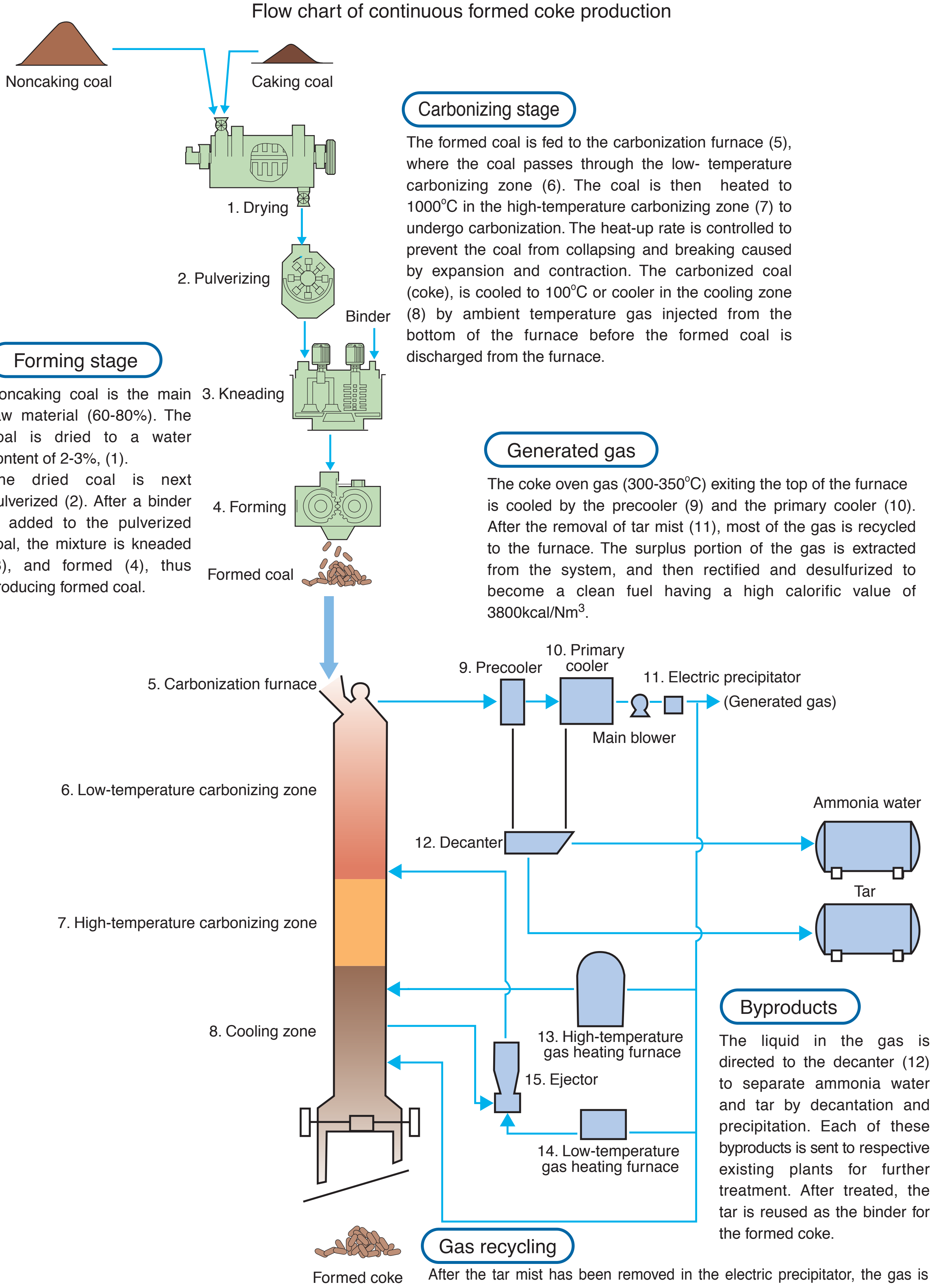
In a large blast furnace, a long and continuous operating test was carried out for 74 days with standard 20% formed coke and a maximum blend of 30% formed coke to confirm that the formed coke can be used in a similar way as chamber oven coke.

4. Research and development progress

Table 1 Research and development progress

Fiscal year	1978	1979	1980	1981	1982	1983	1984	1985	1986
Core	🟩	🟩	🟩	🟩					
Pilot plant test				Construction	Construction	Construction	Test operation	Test operation	Test operation

Flow chart of continuous formed coke production



Forming stage

Noncaking coal is the main raw material (60-80%). The coal is dried to a water content of 2-3%, (1).

The dried coal is next pulverized (2). After a binder is added to the pulverized coal, the mixture is kneaded (3), and formed (4), thus producing formed coal.

Carbonizing stage

The formed coal is fed to the carbonization furnace (5), where the coal passes through the low- temperature carbonizing zone (6). The coal is then heated to 1000°C in the high-temperature carbonizing zone (7) to undergo carbonization. The heat-up rate is controlled to prevent the coal from collapsing and breaking caused by expansion and contraction. The carbonized coal (coke), is cooled to 100°C or cooler in the cooling zone (8) by ambient temperature gas injected from the bottom of the furnace before the formed coal is discharged from the furnace.

Generated gas

The coke oven gas (300-350°C) exiting the top of the furnace is cooled by the precooler (9) and the primary cooler (10). After the removal of tar mist (11), most of the gas is recycled to the furnace. The surplus portion of the gas is extracted from the system, and then rectified and desulfurized to become a clean fuel having a high calorific value of 3800kcal/Nm^3.

Byproducts

The liquid in the gas is directed to the decanter (12) to separate ammonia water and tar by decantation and precipitation. Each of these byproducts is sent to respective existing plants for further treatment. After treated, the tar is reused as the binder for the formed coke.

Gas recycling

After the tar mist has been removed in the electric precipitator, the gas is heated to approximately 1000°C in the high-temperature gas heating furnace (13). It is then injected into the high-temperature carbonizing zone (7). The gas, heated to 450°C in the low-temperature gas heating furnace (14) drives the ejector (15). The ejector (15) draws in the high-temperature gas that was used to cool the coke. Next, the gas is fed to the low-temperature carbonizing zone (6) at a temperature of approximately 600°C.

3A2. Pulverized Coal Injection for Blast Furnaces (PCI)

Research and development: Nippon Steel Corp. and other blast furnace steel makers
Period: Successful introduction of the technology to domestic blast furnaces started in 1981

Technology Overview

1. Background and process overview

The injection of pulverized coal into blast furnaces in Japan began at Nippon Steel Corp.'s Oita No. 1 blast furnace in 1981. Although the main reducing material in blast furnaces is coke, blast furnace operators during and after the 1960s utilized heavy oil as a companion fuel, injecting it through the tuyeres to enhance the productivity, efficiency, and scaling up potential. After the two oil crises, however, the high price of heavy oil forced the producers to switch exclusively to coke, meaning coke was solely relied upon as the reducing material. Nevertheless, there was a desire for an inexpensive heavy-oil-alternative companion fuel to reduce costs and ensure the stable operation of blast furnaces.

To this end, an ARMCO pulverized coal injection system was installed at the Oita No. 1 blast furnace, marking the first introduction of this technology in Japan (Fig. 1). This system featured the following:

1. High-pressure transportation and injection lines with no mechanically rotating components, thereby avoiding wear and tear damage.
2. No recycling of gas, assuring reliable operation.
3. Distribution of pulverized coal fed to individual tuyeres, ensuring uniform distribution utilizing geometrically symmetric flow characteristics of fluid.
4. Drying, pulverizing, and collection of coal conducted in two parallel lines, assuring stable operation of blast furnace.
5. Flow velocity of carrier air and pressure resistance of equipment set in consideration of prevention of fire and explosions.

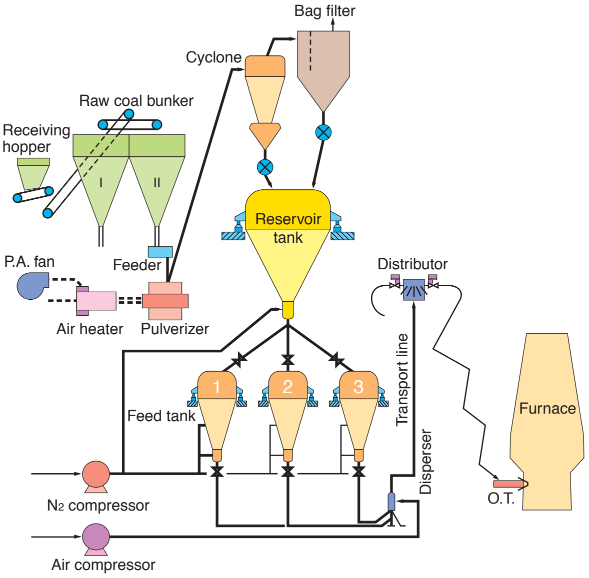


Fig. 1 Process flowchart of pulverized coal injection facility at Oita No. 1 blast furnace

2. Development objectives and technology to be developed

Field tests of the introduced technology had been performed abroad. Considering the differences in facility configurations and scale, as well as operating conditions in Japan versus abroad, a study team conducted tests and investigations, focusing on the following items, and reflected the results in the design.

1. Pulverized coal combustion test: The influence of the grade and size of the pulverized coal, the temperature, pressure, and oxygen rich condition of the air feed, and other variables were evaluated.
2. Model plant test (1 t/hr scale) for coal treatment, transportation, and control.
3. Test to inject coal through a single tuyere into an actual furnace: Combustibility evaluation at the tuyere of an actual furnace, as well as the sampling and evaluation of coke inside the furnace.
4. The distribution of pulverized coal along the circumference: Utilizing a prototype, studies were made to understand the powder flow characteristics and to determine the distribution accuracy.

3. Progress and development results

Considering the heavy oil injection level during an increased production rate period and the experience of long-term results, the capacity of the Oita No. 1 blast furnace was designed for 80 kg/t. Two mill lines, each having 25 t/hr capacity, were installed. After the start of the plant, the equipment operation and injection operation functioned smoothly, establishing a stable production system.

After the success of the Oita No. 1 blast furnace, Godo Steel, Ltd. began operating an exclusively-developed system in 1982. Following the domestic technology, Kobe Steel, Ltd. introduced the U.S. Petrocarb technology and constructed the Kakogawa No. 2 blast furnace and the Kobe No. 3 blast furnace in 1983, as the "Kobelco system." Following that, ARMCO systems were introduced into Nippon Steel's Nagoya No. 1 blast furnace and Nisshin Steel Kure No. 2 blast furnace, which entered commercial operation in 1984. In 1986, pulverized coal injection equipment for blast furnaces was adopted at 16 sites in Japan, accounting for 50% of the market. The number of blast furnaces employing the technology had increased to 25 in 1996. In 1998, all the operating domestic blast furnaces employed the pulverized coal injection equipment, which increased the average domestic pulverized coal ratio to a 130 kg/t level, (Fig. 2). Table 1 shows the various types of injection for the blast furnace pulverized coal equipment. Table 2 shows the highest level attained in Japan for the typical operational index of blast furnaces utilizing pulverized coal injection technology.

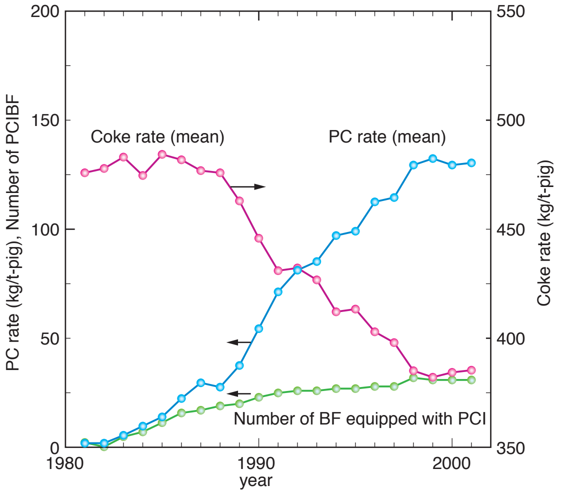


Fig. 2 Increase in installations of pulverized coal injection for blast furnaces technology in Japan

Table 1 Various types of pulverized coal injection equipment for blast furnaces

Process	Type of distribution /transportation	Pneumatic conveying concentration	Velocity	Pipe arrangement/ flow rate control	Users	Investment
Petrocarb	Pneumatic conveying from feed tank directly to each tuyere	Low	High	Carrier gas pressure and flow rate (Downtake)	National Steel, Kobe Steel, JFE (NKK)	Medium
DENKA		Low	High	Same as above, but uptake	JFE (Kawasaki Steel)	Medium
Kuettner		High	Low	Same as above + Flow meter	Thyssen	Large
formerly PW		Medium	Low	Rotary valve	Dunkerque	Medium
Simon Macawber		Low	High	Coal pump	Scunthorpe	Large
ARMCO	Feed tank →Main pipe →Distributor →Tuyere	Low	High	Uniformly distributed to give uniform pressure drop across individual pipes	Nippon Steel Corp., Hoogovens	Small
new PM		High	Low	Uniformly distributed by throttled pipes	Sidmar, Solac Fod	Small
Klockner		High	Low	Same as above	Dunkerque, Taranto	Small
Sumitomo Metal Mining Co., Ltd.		Low	Low	Rotary feeder + uniform pressure drop (one way) distribution	Sumitomo Metal Mining Co., Ltd.	Medium

Table 2 Highest domestic level operational indicies for blast furnaces with pulverized coal injection

	Month and year	Steel works, blast furnace	Coal dust ratio kg/t	Coke ratio kg/t	Reducing material ratio kg/t	Tapping ratio t/d/m^3
Maximum pulverized coal ratio (PCR)	6/98	Fukuyama No. 3 blast furnace	266	289	555	1.84
Minimum coke ratio (CR)	3/99	Kobe No. 3 blast furnace	214	288	502	2.06
Minimum reducing material ratio (RAR)	3/94	Oita No. 1 blast furnace	122	342	464	1.95
Maximum tapping ratio	1/97	Nagoya No. 1 blast furnace	137	350	487	2.63

4. Issues and feasibility of practical application

The average lifespan for domestic coke ovens has reached approximately 30 years, and the importance of pulverized coal injection technology as a companion fuel for blast furnaces increases year by year. Compared with coke, which depends on caking coal, pulverized coal increases the potential for the injection material owing to the adaptability of coal resources. Pulverized coal injection technology has the potential to spur innovations to blast furnaces: recycled materials, such as waste plastics and biomass, as well as recycled ores can be injected with pulverized coal into the furnaces via tuyeres. Thus, the technology is expected to be developed as core blast furnace technology, addressing resource, energy, and carbon dioxide issues.

Reference

Shinjiro Waguri: Ferram, Vol. 8, p. 371, 2003.

3A3. Direct Iron Ore Smelting Reduction Process (DIOS)

Research and development: Japan Coal Energy Center; and Japan Iron and Steel Federation
Period: 1988-1995 (8 years)

Technology Overview

1. Overview

The Direct Iron Ore Smelting Reduction Process (DIOS) directly uses noncaking coal in a powder or granular form, and iron ore without the use of coke or a sintering process, which are normally required in blast furnace processes. The noncaking coal is directly fed to a smelting reduction furnace, while the iron ore is preliminarily reduced before being fed to the furnace, thus producing molten iron.

2. Features

1. Possibility of utilizing inexpensive raw materials and fuel (noncaking coal, in-house dust, etc.)
2. Low operating cost
3. Responds flexibly to variations in production rate
4. Compact and small incremental investment
5. Stable, high-quality supply of iron source available
6. Effective use of coal energy
7. Easy co-production of energy (co-generation)
8. Low environmental load (low SOx, NOx, CO_2, dust generation, no coke oven gas leaks)

3. Results of study

A feasibility study was undertaken on the installation of a new commercial blast furnace plant and of DIOS in a waterfront area. Considering its superiority to the blast furnace process as described below, the feasibility of DIOS can be demonstrated for a 6,000 ton molten iron model production facility (annual production of 2 million tons).

1. Investment cost reduced by 35%.
2. Molten iron production cost decreased by 19%.
3. Coal consumed, 730-750 kg per 1 ton of molten iron production, equivalent to that of the blast furnace process.
4. Net energy consumption decreased by 3 to 4%.
5. CO_2 emissions in the iron making process decreased by 4 to 5%.

4. Research and development progress

Table 1 Research and development progress

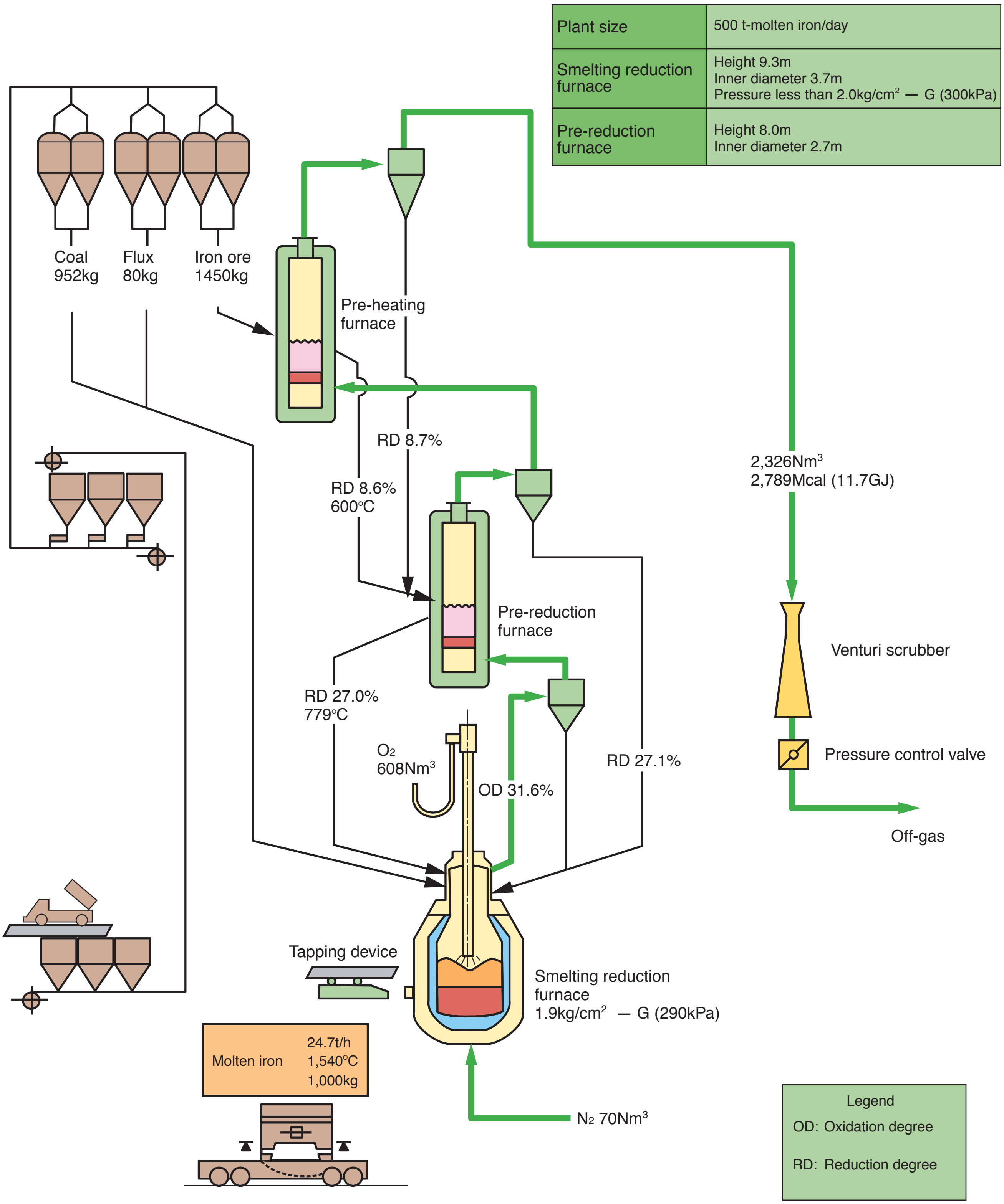
Fiscal year	1988	1989	1990	1991	1992	1993	1994	1995
Core technology study	🟩	🟩	🟩					
Pilot plant test			Construction	Construction	Construction	Construction Test operation	Test operation	Test operation

1) Core technology study (FY1988-FY1990)

Core technologies necessary for the construction of the pilot plant were established. These core technologies include an increase in the thermal efficiency of a smelting reduction furnace (SRF), the technology to be integrated with a preliminary reduction furnace (PRF), the molten slag discharge technology, and the scale-up of an SRF.

2) Pilot plant test (FY1993-FY1995)

1. The possibility of directly using powder, granular ore, and coal was confirmed, and necessary equipment specifications were determined.
2. With various raw materials, the equipment and operating specifications to achieve high thermal efficiency, as an alternative to the blast furnace, were determined.
3. Technology for water-cooling the furnace body was established. A conceptual design and an economic evaluation (FS) for commercial facilities was conducted. The conditions of the facilities and of the operations to prove the superiority versus the blast furnace, as shown in the results of the research, was clarified.



Plant size	500 t-molten iron/day
Smelting reduction furnace	Height 9.3m Inner diameter 3.7m Pressure less than 2.0kg/cm² — G (300kPa)
Pre-reduction furnace	Height 8.0m Inner diameter 2.7m

Fig. 1 Process flowchart for DIOS pilot plant (per 1,000kg of molten iron)

3A4. Super Coke Oven for Productivity and Environment Enhancement toward the 21st Century (SCOPE21)

Research and development: Japan Coal Energy Center; and Japan Iron and Steel Federation
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1994-2003 (10 years)

Technology Overview

1. Background and process overview

The existing coke production process, which rapidly heats the coal at 350°C (low temperature carbonization), as opposed to the old method employing a 1200°C coke furnace, has many problems. These include the unavoidable coal grade limitation necessitating the use of mainly strong caking coke owing to the limitation of coke strength, significant energy consumption due to the characteristics of the process, as well as environmental issues. Coke ovens in Japan have reached their average lifespan of approximately 30 years, and are entering a replacement phase. Given this requirement to replace the ovens, there is a need to develop an innovative, next-generation coke production technology that has the flexibility to handle coal resources, that is energy efficient, that has excellent environmental characteristics, and that is also highly productive. Responding to these needs, a team developed a new coke process.

The SCOPE21 process aims to develop an innovative process responding to the needs of the 21st century in terms of the effective use of coal resources, improvements in productivity, and advancement of environmental and energy technologies. As shown in the Figure 1, the existing coke production process is divided into three stages along the process flow, namely 1) rapid heating of coal, 2) rapid carbonization, and 3) medium-to-low temperature coke reforming. Development was carried out of a revolutionary process with overall balance that pursued the functions of each stage to the utmost.

Currently, SCOPE21 is just one large development project for new coke processes in the world, and it is hoped that it can be put to practical use.

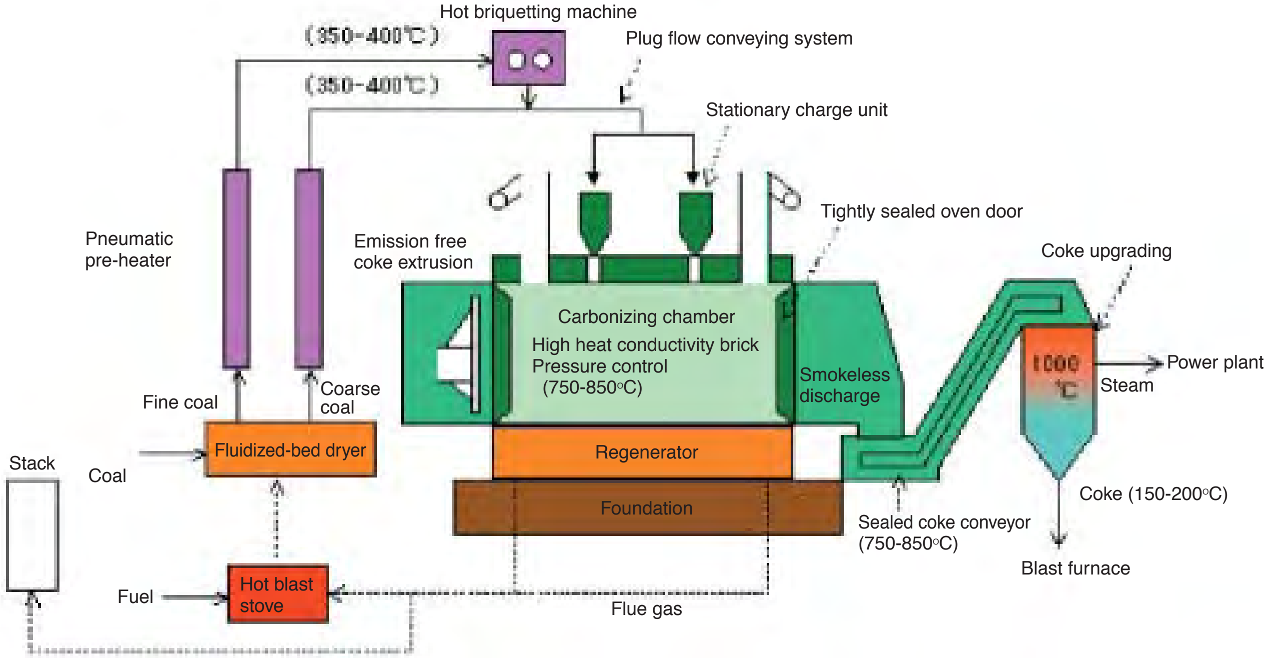


Fig. 1 Process flowchart of next-generation coke oven process

2. Development objectives and technology to be developed

(1) Increasing the ratio of noncaking coal use to 50%

With the aim of increasing the ratio of noncaking coal use to 50%, a level that is currently only approximately 20% (noncaking coal is not the most suitable material for coking), the study develops the technology to increase the bulk density of charging coal through the improvement of caking properties utilizing the rapid heating coal technology and through a process to form the fine coal powder.

(2) Increasing productivity threefold

With an aim to increase the productivity threefold relative to the current level, the study significantly reduces the carbonizing time by increasing the thermal conductivity of the carbonizing chamber wall and by discharging the material at temperatures lower than the normal carbonization point, (medium-to-low temperature carbonization). The resulting insufficient carbonization temperature is compensated for by reheating in the coke dry quenching unit (CDQ) to secure the product quality.

(3) Reducing NOx generation by 30% and achieving smokeless, odorless, and dustless operation

Full-scale prevention of generation of smoke, odor, and dust during coke production is attained through the sealed transportation of coal using a "plug transportation" method, the sealed transportation of coke, and the prevention of gas leaks from the coke oven by applying intra-furnace pressure control. Furthermore, the improved combustion structure of the coke oven reduces NOx generation.

(4) Energy savings of 20%

The amount of energy necessary to produce coke is to be reduced by 20% through 1) the increase in the temperature to start the carbonization by pre-heating the charging coal to a high temperature, 2) the reduction in carbonization heat by reducing the discharging temperature, 3) applying medium-to-low temperature carbonization, and 4) the easy recovery of sensible heat from the generated gas and combustion flue gas owing to the scale reduction of the facilities, resulting in increased productivity.

3. Progress and development results

The project was conducted as a joint effort between Japan Coal Energy Center, and the Japan Iron and Steel Federation. A pilot plant (6 t/hr) was constructed at Nippon Steel Corp.'s Nagoya Works, (See Photo 1), and test operations were conducted.

Photo 1 Pilot plant

Energy Savings and Economic Evaluation

The SCOPE21 process is composed of innovative technologies, enabling the effective use of coal resources, energy savings, and environmental enhancements. As a result, it has great economic advantages over the conventional process.

Reduction of construction costs

	Coke oven	Pretreatment	Common equipment	Total
Conventional	89	---	11	100
SCOPE21	40	25	19	84

Energy savings

Reduction of total energy use by 21% due to the adoption of a pretreatment process with the direct heating of coal and a high-efficiency coke oven with a heat recovery system.

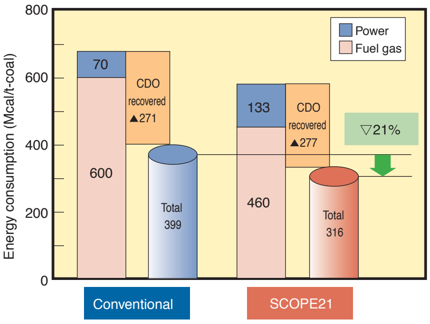
Construction costs

Reduction of 16% by greatly reducing the number of coke ovens even while expanding the coal pretreatment plants and environmental protection measures.

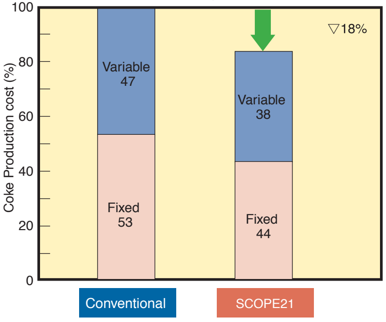
Coke production costs

Reduction of 18% by increasing the poor coking coal ratio and decreasing construction costs even while increasing electricity and fuel gas consumption in the coal pretreatment plant.

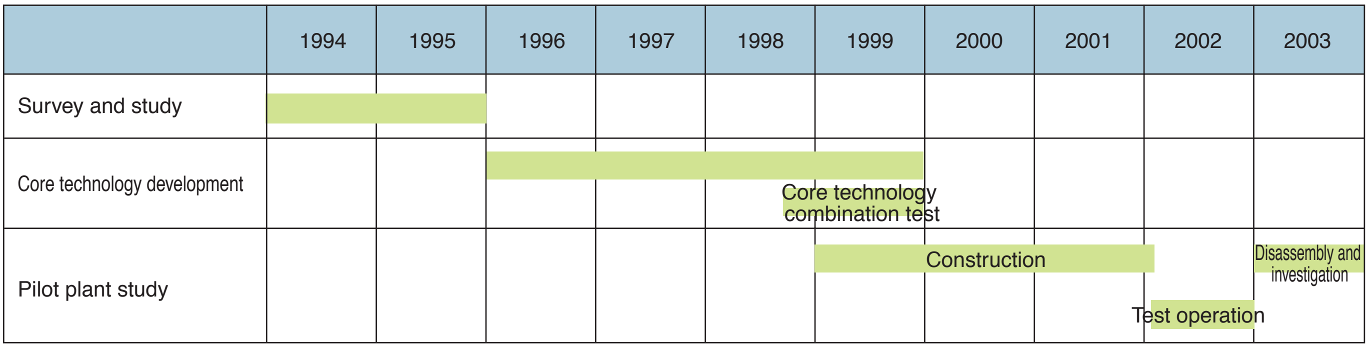
Energy savings: Consumption evaluation



Reduction of coke production costs



SCOPE21 Development schedule



4. Issues and feasibility of practical application

Although there has been progress made in the development of furnace repair technology, coke ovens in Japan continue to age and thus still need to be replaced as scheduled. The developed technology will be introduced to these aging coke ovens, though its introduction will be influenced by economic conditions.

Reference

1) Kunihiko Nishioka et al., Lecture papers at the 12th Coal Utilization Technology Congress, Tokyo, pp.1-2., November 1, 2002.

3A5. Coke Dry Quenching Technology (CDQ)

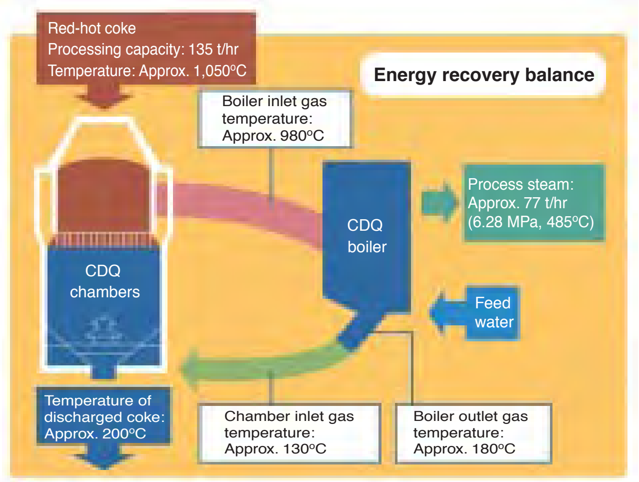
Outline of technology

1. Overview

Overview of CDQ (Coke Dry Quenching) system

The coke oven consists of plate-like carbonization chambers alternately arranged in a sandwich form to achieve higher thermal efficiency in carbonization.

Raw material placed in the carbonization chambers is heated to a temperature between approximately 1100 and 1350°C through the combustion of blast furnace gas in the combustion chambers, which are located on both sides of the carbonization chambers beyond the refractory brick. The heated raw material is not exposed to air for approximately 12 to 14 hours to allow carbonization to proceed. In this process, the fixed carbon contained in the raw material fuses and solidifies to become red-hot coke in the lower section of the carbonization chambers. The volatile component in the raw material vaporizes and decomposes, becoming gas. After escaping from the coke surface, the gas is collected through a pipe located in the upper section of the carbonization chambers. When carbonization is complete, the red-hot coke (approximately 1,050°C) is discharged from the coke oven and then carried to the top of the chambers. The coke is then fed to the chambers and while it descends through the chamber, is cooled with circulating gas blown from the bottom of the chamber. After it has cooled to approximately 200°C, the coke is ejected from the bottom, while the circulating gas that has been heated to 800°C or higher generates high-temperature and high-pressure steam in the boiler. The gas is purified by a dust collector and then sent back to the chambers for recycling. The generated steam is used as process steam or for power generation.



Sample CDQ operating data

Capacity	56t/hr
Coke charge temperature	1000-1050°C
Coke output temperature	200°C
Gas inlet temperature	170°C
Gas outlet temperature	800-850°C
Steam generation	25t/hr
Steam pressure	40kgf/cm^2
Steam temperature	440°C
Total gas volume	84,000Nm^3/hr

Comparison of CDQ coke quality

	Wet quenching	Dry quenching
Water content (%)	2-5	0.1-0.3
Ash content (%)	11.35	11.39
Volatile components (%)	0.50	0.41
Average particle size (mm)	65	55
Powder rate (after cut) (-15 mm%)	10	13
Porosity (%)	49	48
DI^{150}_{15} (%)	83.5	85.5
DI^{150}_{15} (%)	12.9	17.9
Coke strength after small reaction (%)	50	52

Composition of circulating gas

Gas	CO_2	CO	H_2	N_2
Concentration (%)	10-15	8-10	2-3	70-75

CDQ plants

Company	Works	Target furnaces	Coke processing capacity (t/hr) (units)	Plants			Put into service
				Steam (t/hr)	Pressure (kg/cm^2)	Temperature (°C)	
Nippon Steel	Oita	No. 1, 2	190 (1)	112.0	95	520	Oct. 1988
	Oita	No. 3, 4	180 (1)	92.5	93	520	Aug. 1985
	Yahata	No. 4, 5	175 (1)	120.0	75	495	Feb. 1987
	Nagoya	No. 1, 2	106 (1)	65.0	117	525	Sept. 1985
	Nagoya	No. 3	96 (1)	65.0	117	525	Jul. 1995
	Nagoya	No. 4	129 (1)	71.4	117	525	Feb. 1982
Nippon Steel Chemical	Kimizu	No. 1, 2, 3	110 (3)	60.0	95	520	Oct. 1982, Aug. 1983
	Kimizu	No. 4, 5	170 (1)	108.0	95	520	Jan. 1988
Hokkai Steel	Muroran	No. 5, 6	108 (1)	56.5	64	490	Jul. 1981
JFE Steel	East Japan	No. 5	100 (1)	50.0	52.5	436	Apr. 1981
	(Chiba)	No. 6, 7	56 (3)	30.0	25.0	228	Jan. 1977
	East Japan	No. 1	70 (5)	39.0	20	280	Sept. 1976
	(Keihin)	No. 2	70 (3)	39.0	20	280	Jul. 1979
	West Japan	No. 3, 4	100 (2)	64.9	99.0	330	Aug. to Sep. 1983
	(Kurashiki)	No. 5, 6	130 (1)	85.0	99.0	330	Jan. 1986
	West Japan	No. 4	125 (1)	69.0	105	540	Apr. 1986
	(Fukuyama)	No. 5	200 (1)	116.5	85	520	Feb. 1990
		No. 3	185 (1)	111.7	86	523	Jan. 1997
Sumitomo Metal Industries	Kagoshima	No. 1ABCD	195 (1)	100.0	105.0	545	Mar. 1986
		No. 2AB	150 (1)	65.0	105.0	545	Jan. 1984
		No. 2CD	130 (1)	65.0	105.0	545	Nov. 1981
	Wakayama	No. 6	100 (1)	60.0	102	540	Apr. 1994
Kansai Coke and Chemicals	Kakogawa	No. 1, 2	140 (1)	84.0	112.0	556	Jun. 1987
		No. 3, 4	150 (1)	98.0	112.0	556	Oct. 1998
Nakayama Steel Works	Funamachi	No. 2	58 (1)	31.0	65	490	May 1991

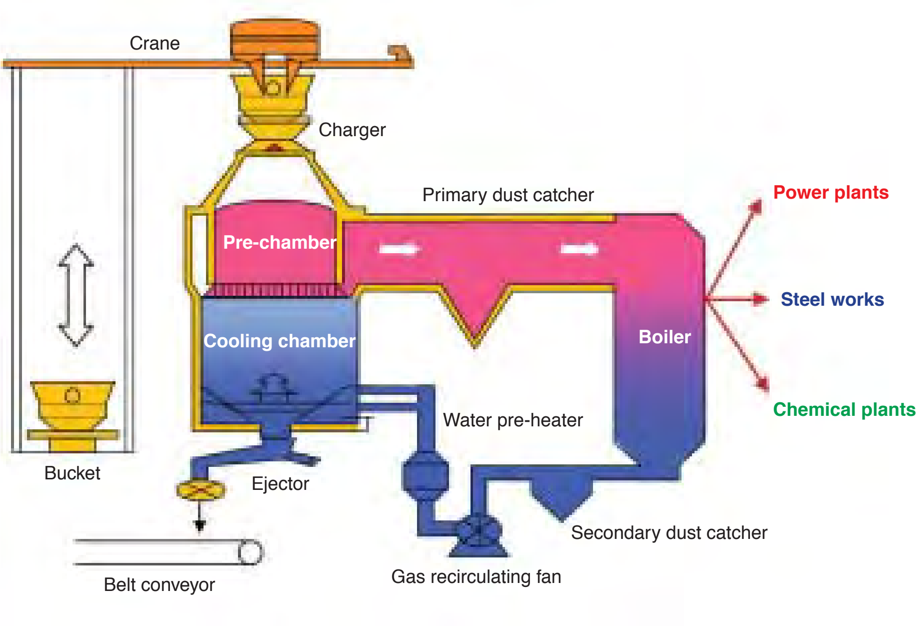
2. Features of CDQ system

Conventional system

The red-hot coke extruded from the coke oven is cooled by spraying it with water. The water used for cooling is vaporized and released into the atmosphere. An issue with this conventional system is the energy loss when the thermal energy of the red-hot coke is converted into heat that is vaporized and released unused. Another drawback is that the conventional system also produces airborne coke dust.

CDQ system

In the CDQ system, the red-hot coke is cooled by gas circulating in an enclosed system, thereby preventing the release of airborne coke dust. The thermal energy of the red-hot coke, which is lost in the conventional system, is collected and reused as steam in the CDQ system. This technology uses less fossil fuel and results in lower CO_2 emissions, thereby contributing to the prevention of global warming.



CDQ process flow

3. Dissemination of coke dry quenching (CDQ) systems

CDQ systems have been installed in many steel works and coke ovens in Japan as energy-efficient, environmentally-friendly technology.
Through NEDO model projects, the effectiveness of CDQ has also been recognized in China. The Chinese government specified CDQ technology as one of the targets in the Tenth 5-year plan in 2000.
Steel works in Hanfang, Beijing, Chengde and Hangzhou have already introduced Japanese CDQ systems.

Reduction of CO_2 emissions (expected energy conservation: heat collected from generated steam = 604.3 Tcal/year)

Scenario	CO_2 emissions ($t\text{-}CO_2$/year)
CO_2 emissions from CDQ project	1,771,569
Baseline CO_2 emissions	1,908,311
Expected reduction of CO_2 emissions	136,742

4. Future prospects

The Asian region is expected to continue increasing its production of crude steel. Efforts to introduce CDQ are being made in China and India. CDQ is an established technology that can help Japan to achieve its Kyoto Protocol target via the use of CDM projects.

3B1. Fluidized-bed Advanced Cement Kiln System (FAKS)

Technology overview

1. Features

The Fluidized-bed Advanced Cement Kiln System (FAKS) efficiently combusts low-grade coal, significantly reduces NOx emissions, and increases the heat recovery efficiency between solids and gases discharged from the process. This is accomplished by leveraging the advantages of the fluidized-bed process, including the combustion efficiency, and the heat transfer efficiency, as well as the particle dispersion and granulation features. Thus, the ultimate objectives of the development are to contribute to global environmental conservation, energy conservation, and to fulfill demands for various types and/or special grades of cement.

Photo 1 Clinker produced from a fluidized-bed kiln

Photo 2 Overview of 200 t/day plant

2. Technology overview

A FAKS includes a fluidized-bed cement kiln and a two-stage cooler. The fluidized-bed cement kiln reduces the raw material to a specific size for melting it into high quality cement, and then sinters the granulated raw material at a high temperature. The two-stage cooler combines a quenching cooler and a packed-bed, slow-cooling cooler to increase the heat recovery efficiency. The most important technology in the system is the granulation control technology. Compared with conventional technology, which required that seed clinker be fed from the outside and which required control of the granulation process thus allowing high temperature raw material powder to adhere and accumulate to the seed clinker, FAKS employs a first-ever "self-granulation" process. Self-granulation is the process where granule cores are generated through the agglomeration of a portion of the raw material, allowing the rest of the raw material to adhere and grow on the core in order to control granulation. The fluidized-bed cement kiln furnace integrates two major technologies to control the granulation: a raw material injection unit, and a bottom classification and discharge unit.

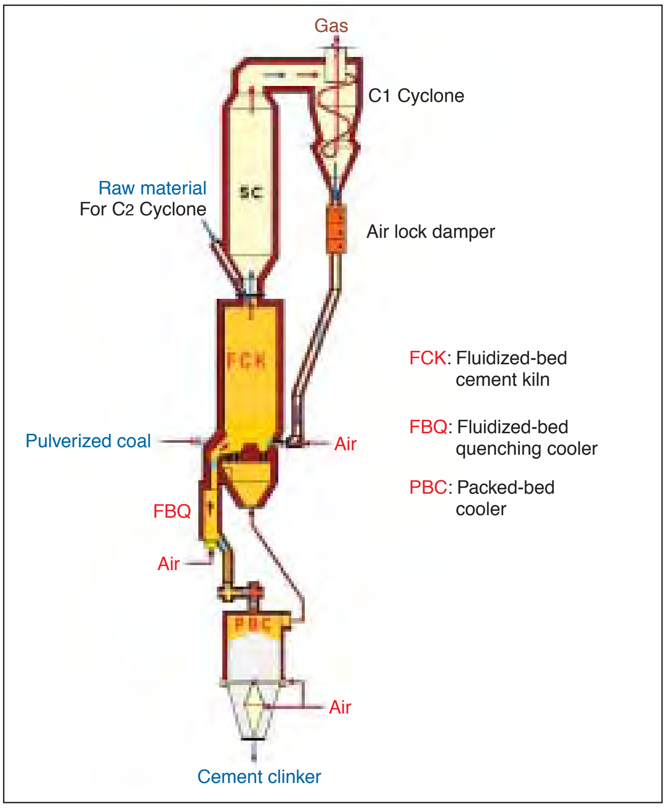


Fig. 1 FAKS process flowchart

3. Demonstration site and application

1) 200 t/day demonstration

[1] Demonstration site: Sumitomo Osaka Cement Co., Ltd.'s Tochigi plant

[2] Application: Cement production

[3] Development period: 1996 to 1998

2) 1,000 t/day demonstration

[1] Demonstration site: Shandong Paoshan Biological Building Materials Co., Ltd.
Liubo City, Shandong Province, China

[2] Application: Cement production

[3] Development period: 2005 to 2007

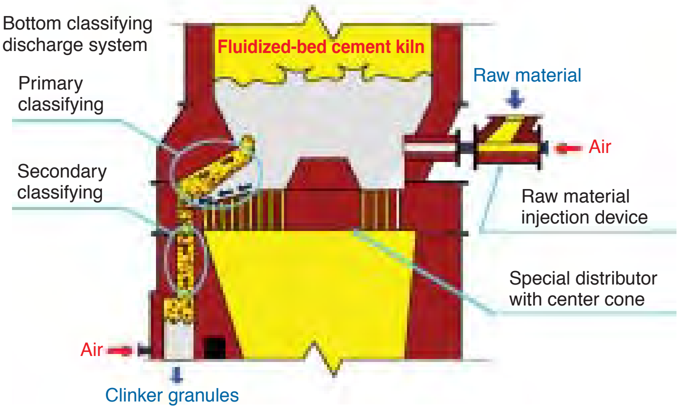


Fig. 2 Key technology

4. Demonstration site and application

A basic study of FAKS technology was originally launched in 1984 as a voluntary project by Kawasaki Heavy Industries, Ltd. and Sumitomo Osaka Cement Co., Ltd. Based on the results of the study, research and development have been sponsored since 1986 under a Coal Production and Utilization Technology Promotion Grant project of the Agency of Natural Resources and Energy of the Ministry of International Trade and Industry. In June of 1989, a 20 t/d pilot plant was constructed jointly by Japan Coal Energy Center, Kawasaki Heavy Industries, Ltd., and Sumitomo Osaka Cement Co., Ltd. The plant was subsequently put into test operation. The basic planning and design of a 200 t/d plant were jointly undertaken by Japan Coal Energy Center, and the Japan Cement Association in April 1993. This scaled-up plant was put into test operation for commercialization in February 1996. After the system was validated, test operations of the plant were completed at the end of December 1997.

NEDO also launched a joint demonstration project for a 1,000 t/d FAKS plant at Shandong Paoshan Biological Building Materials Co., Ltd. in Liubo City, Shandong Province, China, as an International Coal Utilization Project in May 2005.

5. Issues

A performance comparison between the conventional technology and FAKS for a 1,000 t/d commercial plant is shown in the Table 1 below. FAKS is expected to be commercially adopted as an innovative, alternative cement production technology.

Table 1 Comparison of environmental improvement effects of FAKS vs. a rotary kiln type process at a 1,000 t/d plant

Discharge quantity		Rotary Kiln & AQC	FAKS
NO_2 1% N and10% O_2 content in coal Emissions Rotary Kiln & AQC FAKS	Emissions (mg/Nm^3)	708	476
	Annual emissions (tons-NO_2/year)	341	233
CO_2* depends on electric power and fuel consumption	Emissions (g/Nm$^{3)}$	245	220
	Annual emissions (tons-CO_2/year)	118x10^3	108x10^3
Basis of calculation			
Production capacity	tons-clinker/day	1,000	1,000
	tons-cement/day	1,050	1,050
Annual operating time	days/year	330	330
Heat consumption	kJ/ton-clinker	3,411x10^3	2,993x10^3
Power consumption	kWh/ton-clinker	27	36
Exhaust gas specific quantity	Nm^3/kg-clinker	1.46	1.49
Lower calorific value of coal	kJ/kg-coal	25,116	25,116

*Based on IPCC: Guideline for National Greenhouse Gas Inventories, Reference Manual Carbon Emission Coefficient/Basic Calculation;
Carbon Emission Factor = 26.8 tC/TJ, Fraction of Carbon Oxidized = 0.98

Reference

1) Isao Hashimoto, Tatsuya Watanabe, et al., Development of Fluidized Bed Advanced Cement Kiln Process Technology (Part 9), The 8th Coal Utilization Technology Congress, Japan, September 1998.

3B2. New Scrap Recycling Process (NSR)

Research and development: Japan Coal Energy Center; Nippon Sanso Corp.; and JFE Steel Corp.
Project type: Coal Production and Utilization Technology Promotion Grant
Period:1992-1997 (6 years)

Technology overview

1. Background

In Japan, approximately 30 million tons of iron scrap are recycled annually, and most is melted in arc furnaces, which consume a significant amount of electric power. The energy efficiency of an arc furnace is as low as approximately 25% (converted to primary energy, taking into account power generation and transmission efficiency). Given this, there is a need for a more energy-efficient melting process. In response, the NSR process employs technology that melts metals such as iron scrap utilizing high-temperature energy from the direct combustion of pulverized coal by oxygen instead of electric power. The NSR process was developed with the objective of significantly increasing the energy efficiency of the melting process relative to that of conventional technology.

2. Development timetable

Development was promoted by a joint team from Japan Coal Energy Center, Nippon Sanso Corp., and NKK Corp. (now JFE Steel Corporation). The main subjects of development were the furnace structure and the burner arrangement to attain high-efficiency melting. The study began with a batch smelter. With the results of the batch smelter, a continuous melting furnace was developed, with the objective of improving the energy efficiency.

Table 1 Development timetable

		1992	1993	1994	1995	1996	1997
Survey		🟩					
Batch-furnace	Bench scale (1 t/batch)	🟩	🟩	🟩			
	Pilot plant scale (5 t/batch)				🟩	🟩	
Continuous furnace (pilot plant scale: 6 t/hr)						🟩	🟩

3. Overview of process and results of study

Figure 1 shows the process overview of the continuous melting furnace. The melting furnace consists of three sections: melting, basin, and holding, each of which functions separately. Each section has a pulverized coal oxygen burner. The oxygen supplied to the burner is preheated to temperatures of 400-600°C by an oxygen preheater to combust the pulverized coal. Using the above-described system, even slow-burning pulverized coal can be rapidly combusted, with efficiency similar to that of liquid fuels, such as heavy oil. Raw materials fed from the top of the furnace are directly melted by the burner in a shaft-shaped melting section in the lower part of the furnace. The melted raw material flows through the basin section and enters the holding

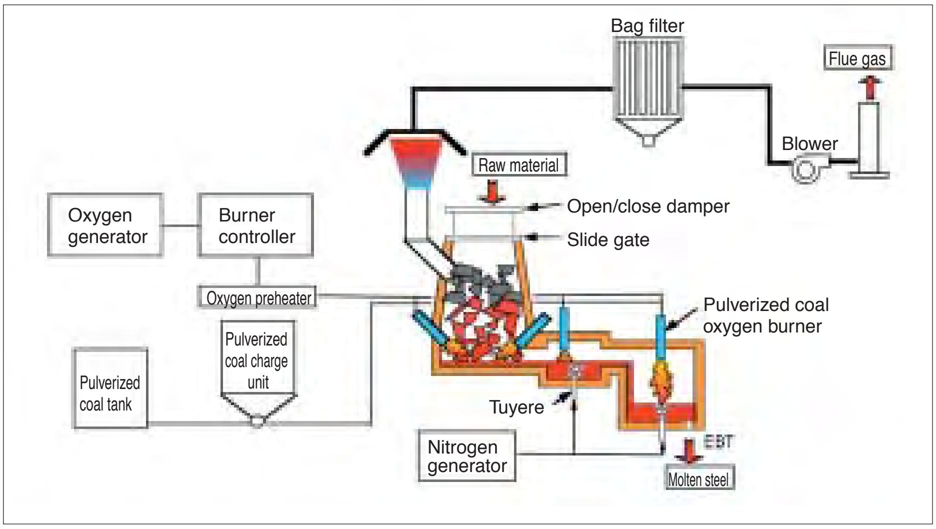


Fig. 1 NSR process flowchart

Fig. 2 Pilot plant (6t/hr)

section. The molten steel is soaked in the basin section. The carbon content of the molten steel in the basin section can be controlled by injecting powder coke into the furnace. The holding section stores the molten steel for a specified period, and rapidly heats the molten steel to approximately 1,600°C, and then taps the molten steel through an EBT system. Molten steel agitation gas is injected from the bottom of the respective furnaces to the basin section and the holding section to accelerate the heat transfer from flame to molten steel, thereby enhancing the slag-metal reaction. All the combustion gas coming from the individual sections passes through the melting section, and is vented from the furnace top after being used to preheat the raw material in the melting section. The raw material is continuously fed from the furnace top and melted in the furnace. Tapping from the holding section is conducted intermittently.

The process effectively utilizes the heat transfer characteristics of oxygen burners, and achieves high-efficiency melting. Figure 3 shows a comparison of melting energy between the NSR process and the arc furnace. Electric power (oxygen is also added because it is produced by electricity) is included in the primary energy and includes power generation and transmission losses. Compared with a standard arc furnace, melting energy was reduced by 40%, dramatically improving energy efficiency. Furthermore, the process achieved highly superior results relative to the conventional process from an environmental perspective, such as a significant suppression of dust (excluding the ash in pulverized coal) and of dioxins, due to the control of the intrafurnace atmosphere.

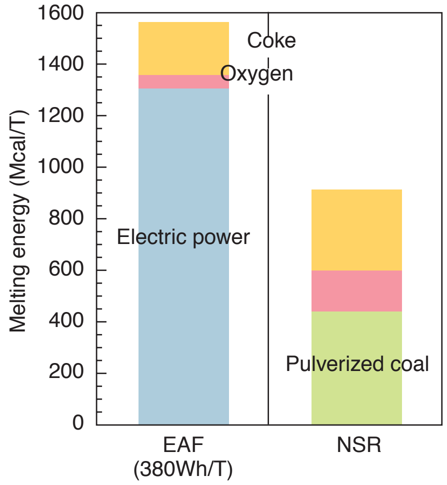


Fig. 3 Comparison of melting energy

4. Toward practical application

The study team completed the design for actual scale facilities. Due to the influence of the current poor economy in the electric furnace industry, however, the process has not been brought into practical application. Nevertheless, since the process is a non-power melting technology, which, even globally, is quite rare, and because of the strong advantage of being unaffected by the electric power infrastructure, the study team continues to make efforts toward commercialization in Japan and abroad.

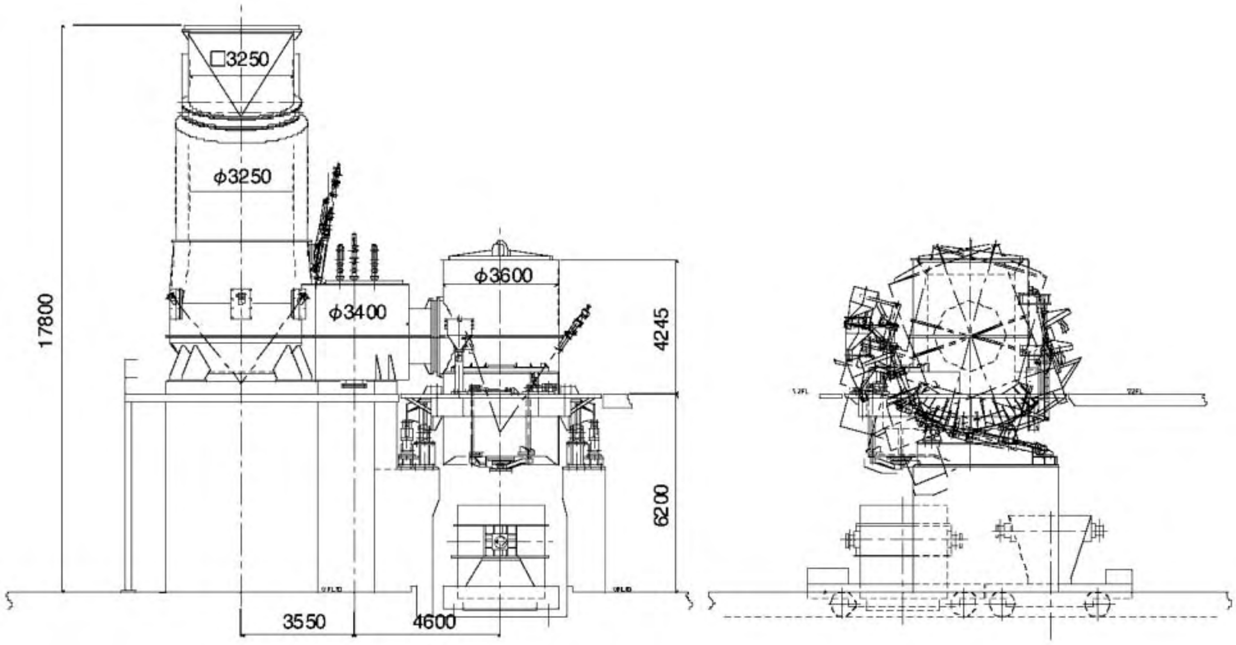


Fig. 4 Schematic for commercial-scale plant (50 t/hr)

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2) Hiroshi Igarashi, Nobuaki Kobayashi, and Hiroyuki Nakabayashi: Technical Bulletin of Nippon Sanso Corp., (19) pp. 30-37, 2000.

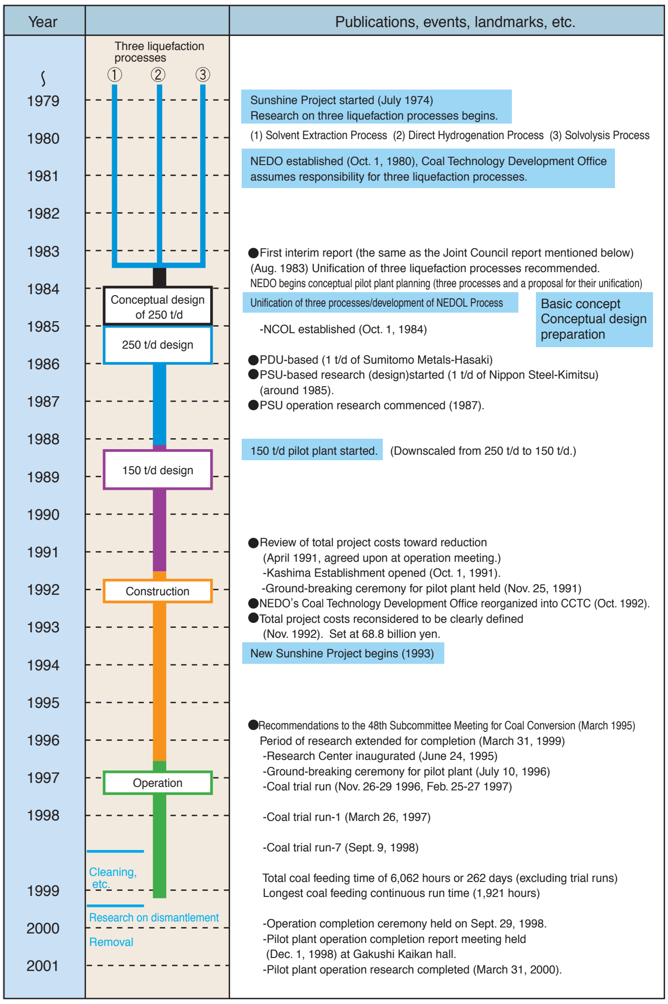
4A1. Coal Liquefaction Technology Development in Japan

Technology overview

1. Background of coal liquefaction technology development

Since the Industrial Revolution, coal has been an important source of energy. Coal consumption surpassed that of firewood and charcoal for the first time in the latter half of the nineteenth century, making coal a major source of energy. In Japan, coal also became a primary energy source in the twentieth century. In the 1960s, however, coal's preeminence gradually faded as it was replaced by easier-to-use oil. It was after the oil crises of 1973 and 1978 that coal was thought of highly once again. With the oil crises as a turning point, the development of oil-alternative energy, particularly coal utilization technology, came into the spotlight amid calls for a diversification of energy sources. During that time, the liquefaction of coal, which had been positioned as the strongest oil-alternative energy contender because of huge coal reserves, was undergoing development in many countries. Research in Germany and the United States involved pilot plants with the capacity to treat hundreds of tons of coal per day. In Japan as well, development of coal liquefaction technology was being promoted under the Sunshine Project mainly by the New Energy and Industrial Technology Development Organization (NEDO). Despite being a decade or so behind Germany and the United States, slow but steady development progress in Japan led to the successful completion of a 150 t/d-scale pilot plant for the liquefaction of bituminous coal in 1998. This drew Japan equal with Germany and the United States and also established state-of-the-art coal liquefaction technology. Coal-producing countries, such as China and Indonesia, have also expressed strong interest in the commercialization of coal liquefaction technology, with high expectations for its future development.

History of NEDOL Process



Sunshine Project started (July 1974)
Research on three liquefaction processes begins.

(1) Solvent Extraction Process (2) Direct Hydrogenation Process (3) Solvolysis Process

NEDO established (Oct. 1, 1980), Coal Technology Development Office assumes responsibility for three liquefaction processes.

●First interim report (the same as the Joint Council report mentioned below) (Aug. 1983) Unification of three liquefaction processes recommended.
NEDO begins conceptual pilot plant planning (three processes and a proposal for their unification)

Unification of three processes/development of NEDOL Process

Basic concept
Conceptual design
preparation

-NCOL established (Oct. 1, 1984)

●PDU-based (1 t/d of Sumitomo Metals-Hasaki)
●PSU-based research (design)started (1 t/d of Nippon Steel-Kimitsu) (around 1985).
●PSU operation research commenced (1987).

150 t/d pilot plant started. (Downscaled from 250 t/d to 150 t/d.)

●Review of total project costs toward reduction (April 1991, agreed upon at operation meeting.)
-Kashima Establishment opened (Oct. 1, 1991).
-Ground-breaking ceremony for pilot plant held (Nov. 25, 1991)
●NEDO's Coal Technology Development Office reorganized into CCTC (Oct. 1992).
●Total project costs reconsidered to be clearly defined (Nov. 1992). Set at 68.8 billion yen.

New Sunshine Project begins (1993)

●Recommendations to the 48th Subcommittee Meeting for Coal Conversion (March 1995)
Period of research extended for completion (March 31, 1999)
-Research Center inaugurated (June 24, 1995)
-Ground-breaking ceremony for pilot plant (July 10, 1996)
-Coal trial run (Nov. 26-29 1996, Feb. 25-27 1997)

-Coal trial run-1 (March 26, 1997)

-Coal trial run-7 (Sept. 9, 1998)

Total coal feeding time of 6,062 hours or 262 days (excluding trial runs)
Longest coal feeding continuous run time (1,921 hours)

-Operation completion ceremony held on Sept. 29, 1998.
-Pilot plant operation completion report meeting held (Dec. 1, 1998) at Gakushi Kaikan hall.
-Pilot plant operation research completed (March 31, 2000).

2. History of coal liquefaction technology development in Japan

2.1 Dawning of coal liquefaction technology development

Between around 1920 and 1930, the South Manchurian Railway Co., Ltd. started basic research on coal liquefaction using the Bergius Process, and around 1935 initiated operation of a bench-scale PDU (process development unit) plant. Based on this research, a plant with annual production capacity of 20,000 tons of coal oil was built at the Wushun coal mine, China, and operated until 1943. In the meantime, Korean Artificial Petroleum Co., Ltd. succeeded, between 1938 and 1943, in the continuous operation of a direct coal liquefaction plant capable of treating 100 t/d of coal at its Agochi factory. The production of coal oil at both of the above-mentioned plants was suspended at the request of the military so that the plants could be used for the hydrogenation of heavy oil or to produce methanol. Around 1930, besides the direct coal liquefaction method (Bergius Process), a second process, the Fischer-Tropsch Process, was used as an indirect coal liquefaction method to study coal liquefaction technology and to produce synthetic oil. The Fischer-Tropsch Process was introduced into Japan upon its announcement in Germany in 1935 and, in 1937, the construction of a plant commenced in Miike. This oil synthesis plant was completed in 1940, with an annual production capacity of 30,000 tons of coal oil. Under the backdrop of war, production of synthetic oil was continued until the end of World War II.

2.2 Post-war research on coal liquefaction

Immediately after the war, the U.S. Armed Forces Headquarters banned coal liquefaction research, alleging that it was military research. In 1955, coal liquefaction research was resumed at national laboratories and universities. This was not, however, research on coal oil production but the production of chemicals from the high-pressure hydrocracking of coal. This research continued until around 1975. The Sunshine Project was inaugurated in 1974 on the heels of the first oil crisis, encouraging efforts to devise liquefaction technology unique to Japan as part of an oil-alternative energy development program. Under the Sunshine Project, technological development was undertaken for three coal liquefaction processes, (Solvolysis, Solvent Extraction, and Direct Hydrogenation), to liquefy bituminous coal. The R&D of brown coal liquefaction processes began at the end of 1980.

2.3 Amalgamation of three coal liquefaction processes

With the oil crises as an impetus, coal liquefaction technology development was incorporated for further promotion into the Sunshine Project based on Japan's international obligations and the need for a large, stable supply of liquid fuel, the diversification of energy sources and the development of oil-alternative energy. In 1983, NEDO (New Energy Development Organization, now New Energy and Industrial Technology Development Organization) assembled the R&D results thus far obtained from the three bituminous coal liquefaction processes as follows:

(1) Results of Direct Hydrogenation Process: Under certain reaction conditions, the better the catalyst function, the higher the liquid yield rate.

(2) Results of Solvent Extraction Process: Hydrogen offers liquefaction under mild conditions.

(3) Results of Solvolysis Liquefaction Process: To focus on the acquisition of light oil, it is effective to thicken the circulation solvent. These three processes were amalgamated on the strength of their features into the NEDOL Process.

2.4 Bituminous coal liquefaction technology development (NEDOL Process)

Bituminous coal liquefaction technology development is described in [4A-2].

2.5 Brown coal liquefaction technology development (BCL Process)

Brown coal liquefaction technology development is described in [4A-3].

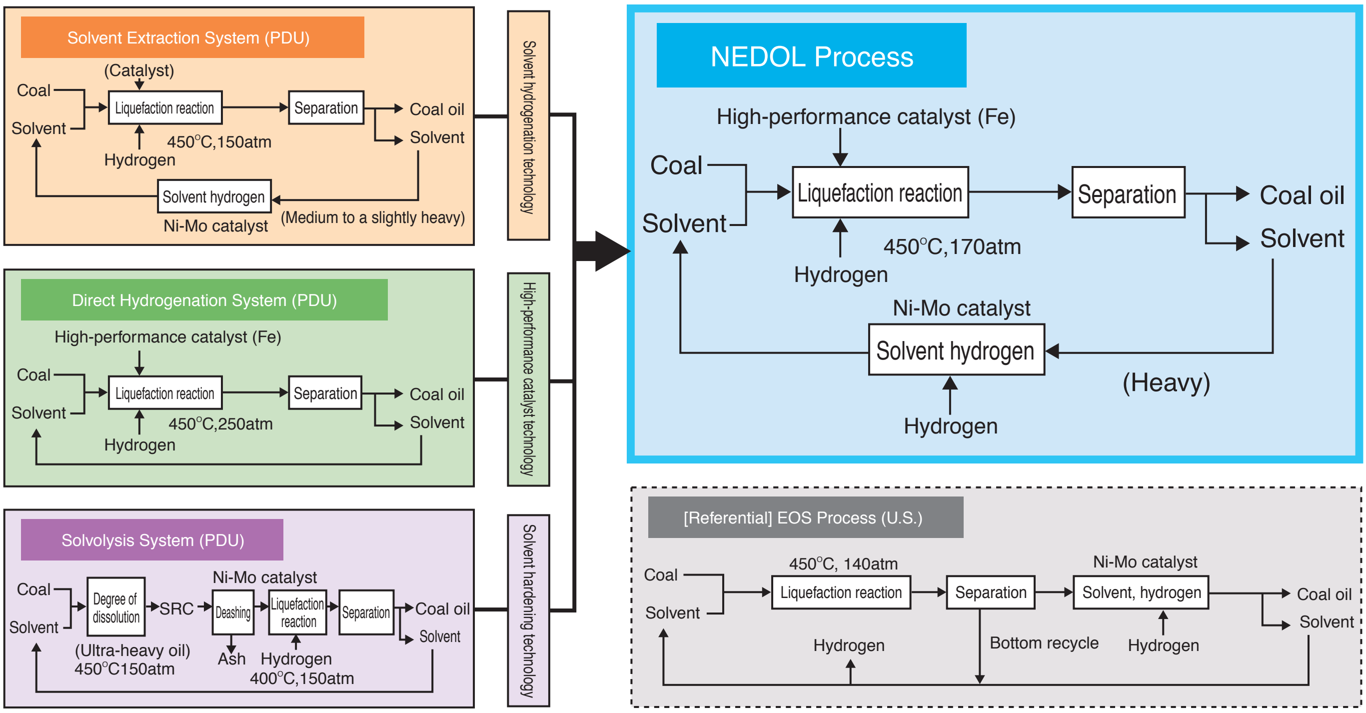


Fig. 1 Basic philosophy of NEDOL Process

References
1) Sadao Wasaka: "Bulletin of The Japan Institute of Energy," 78 (798), 1999.
2) "Development of Coal Liquefaction Technology - A Bridge for Commercialization," Nippon Coal Oil Co., Ltd.
3) Haruhiko Yoshida: "Coal Liquefaction Pilot Plant," New Energy and Industrial Technology Development Organization.

4A2. Bituminous Coal Liquefaction Technology (NEDOL)

Research and development: New Energy and Industrial Technology Development Organization; Nippon Coal Oil Co., Ltd. [Sumitomo Metal Industries, Ltd.; Idemitsu Kosan Co., Ltd.; Nippon Steel Corp.; Chiyoda Corp.; JFE Steel Corp.; Hitachi Ltd.; Mitsui Coal Liquefaction Co., Ltd.; Mitsui Engineering & Shipbuilding Co., Ltd.; Mitsubishi Heavy Industries, Ltd.; Kobe Steel, Ltd.; Japan Energy Co., Ltd.; Sumitomo Metal Mining Co., Ltd.; Asahi Chemical Industry, Co., Ltd.; Toyota Motor Corp.; Sumitomo Coal Mining Co., Ltd.; Nissan Motor Co., Ltd.; The Japan Steel Works, Ltd.; Yokogawa Electric Corp.; and The Industrial Bank of Japan, Ltd.]
Project type: Development of bituminous coal liquefaction technology, and development of NEDOL Process
Period: 1983-2000 (18 years)

Technology overview

1. Overview of NEDOL Process development

The conceptual design of a 250 t/day pilot plant began in FY1984. Owing to changes in economic conditions, however, the design of a 150 t/d PP began in FY1988. As a support study to the pilot plant, the operational study of a 1 t/d process support unit (PSU) was carried out. The 1 t/d PSU, constructed in FY1988 at Kimitsu Ironworks of Nippon Steel Corp., consisted of four stages: coal storage and pretreatment, liquefaction reaction, liquefied coal distillation, and solvent hydrogenation. Over the ten-year period from FY1989 to FY1998, a joint study team from Nippon Steel Corp., Mitsui Coal Liquefaction Co., Ltd., and Nippon Coal Oil Co., Ltd. conducted operational studies on nine coal grades under 72 conditions. Through the 26,949 hours of cumulative coal slurry operations, the stability and the overall operability of the NEDOL Process were confirmed, and optimization of the process was established. Finally, the necessary design data was acquired. Construction of the 150 t/d pilot plant was launched in 1991 at Sumitomo Metal Industries, Ltd.'s Kashima Steelworks (Kashima City, Ibaraki), requiring nearly five years for completion. The pilot plant consisted of five main facilities: the coal treatment unit, the consisted liquefaction reaction unit, the liquefied coal distillation unit, the solvent hydrogenation unit, and the hydrogen production unit.

2. Evaluation of NEDOL Process

Figure 1 shows the progress of coal liquefaction technology since before World War II, expressed by the relation between the severity of the liquefaction reaction and the yield of coal-liquefied oil by generation. As seen in Figure 1, the NEDOL Process is competitive with the processes in Europe and the United States in terms of technology, economics, and operational stability, and thus the NEDOL Process is one of the most advanced processes in the field, reaching a position to shift to commercialization in the shortest amount of time.

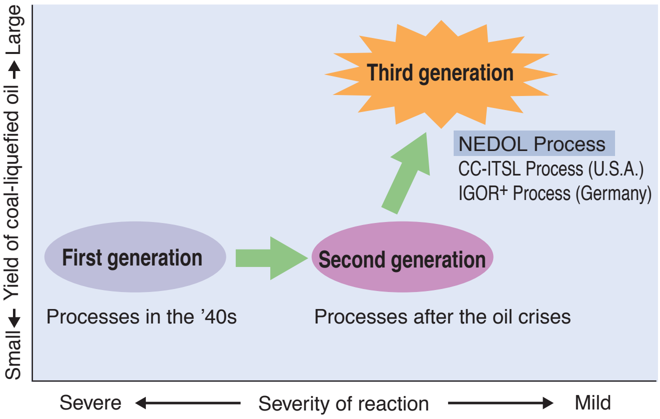


Fig. 1 Relation between the severity of liquefaction reaction and the yield of coal-liquefied oil

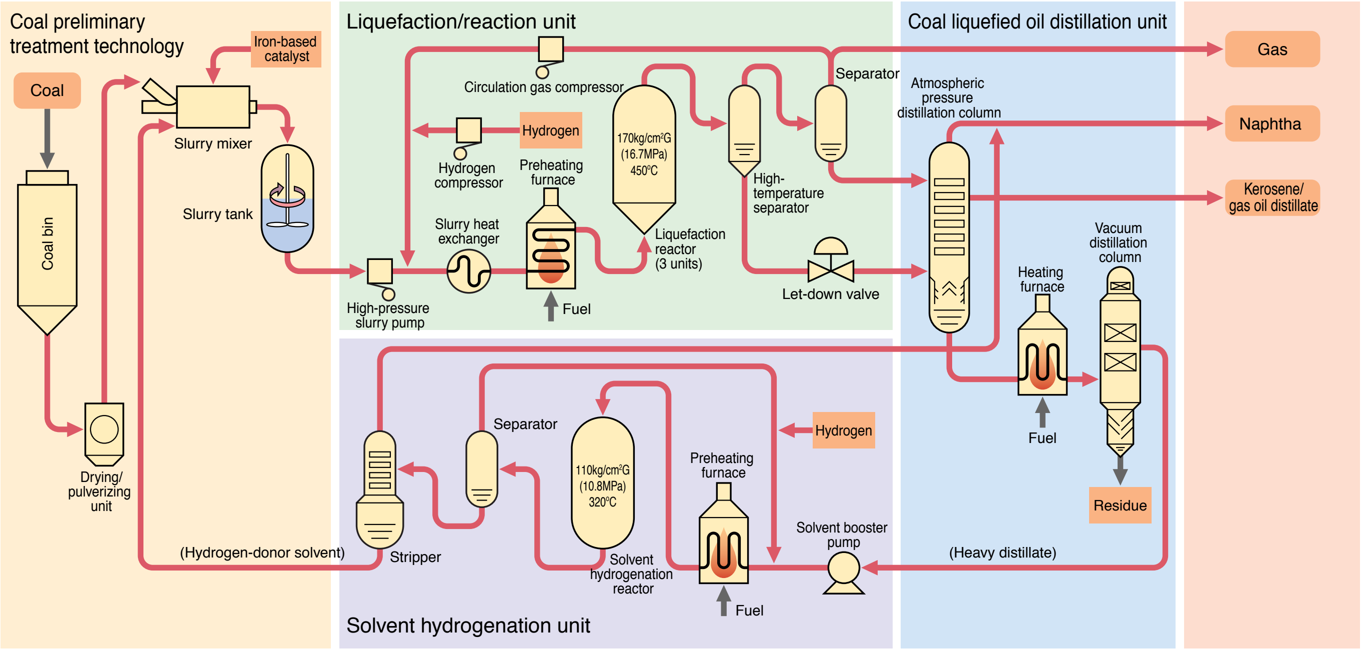


Fig. 2 Bituminous coal liquefaction process flowchart

3. Features of NEDOL Process

The NEDOL Process is a coal liquefaction process developed exclusively in Japan. The process has integrated the advantages of three bituminous liquefaction processes (Direct Hydrogenation Process, Solvent Extraction Process, and Solvolysis Process), thus providing superiority in both technology and economics. The advantages of the NEDOL Process include:

(1) attaining high liquid yield under mild liquefaction reaction conditions owing to the iron-based fine powder catalyst and to the hydrogen-donating solvent;

(2) producing coal-liquefied oil rich in light distillate;

(3) assuring high process stability because of the highly reliable core process stages; and

(4) applicability to a wide range of coal ranks, ranging from sub-bituminous coal to low coalification grade bituminous coal.

Catalysts			
Liquefaction catalyst		Hydrogenation catalyst	
Catalyst composition Fe (wt%)	48.2	Catalyst composition Fe (wt%)	Ni-Mo/γAl$_2$O$_3$
S (wt%)	51.0	Specific surface area (m^2/g)	190
Other (wt%)	0.8	Micropore volume (ml/g)	0.7
Specific surface area (m^2/g)	6.1	Mean micropore size (nm)	14.5
Size of pulverized catalyst [D^{50}](μm)	0.7-0.8		

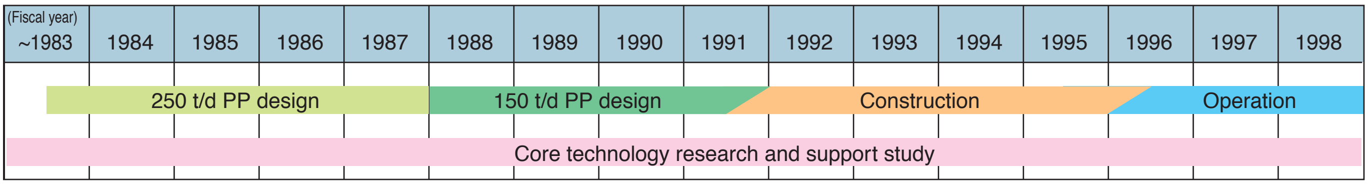
4. Typical reaction conditions of NEDOL Process

Liquefaction reaction				Solvent hydrogenation reaction			
Temperature	450°C	Slurry concentration	40 wt% (dry coal basis)	Temperature	320°C	Gas/solvent ratio	500Nm^3/t
Pressure	170kg/cm^2·G	Slurry retention time	60 min	Pressure	110kg/cm^2·G	Hydrogen concentration in recycle gas	90 vol%
Type of catalyst	Iron-base fine powder catalyst	Gas/slurry ratio	700Nm^3/t	Kind of catalyst	Ni-Mo-Al$_2$O$_3$		
Added amount of catalyst	3 wt%(dry coal basis)	Hydrogen concentration in recycle gas	85 vol%	LHSV	1 hr$^{(-1)}$		

5. Pilot plant: Objectives and achievements

Development objectives	Target	Achievements
1. Yield of coal-liquefied oil	For standard coal, 50 wt% or higher yield of light to medium oils, and 54 wt% of higher total yield	With standard coal, attained 51 wt% yield of light to medium oils, and 58 wt% of total yield
2. Slurry concentration	40-50 wt% of coal concentration in slurry	Stable operation achieved at 50 wt% of coal concentration in slurry
3. Added amount of catalyst	2-3 wt% (dry-coal basis) of added amount of iron sulfide-base catalyst	Operation conducted in a range from 1.5 to 3 wt% of added amount of iron sulfide-base catalyst
4. Continuous operation time	1,000 hours or more for standard coal	Continuous operation of 80 days (1,920 hours) achieved with standard coal
5. Range of applicable coal grades	Three coal ranks or more	Operation conducted with a wide range of coalification ranks, namely Adaro coal, Tanitohalm coal, and Ikejima coal

6. Research and development timetable of NEDOL Process pilot plants



7. Research and development results

All the acquired data, including the pilot plant data, the basic research data, and the support study data, were summarized in a technology package in preparation for practical application. At the Development and Assessment Committee Meeting for Bituminous Coal Liquefaction Technology in the Assessment Work Group of the Industrial Technology Council, held on December 22, 1999, the NEDOL Process was highly evaluated: "The NEDOL Process is at the highest technology level in the world, and has reached the stage where worldwide diffusion is expected." Thus, the development of coal liquefaction technology in Japan has already exited the research and development stage and entered the practical application stage. Furthermore, the developed materials and new processes are expected to significantly influence development in other industries.

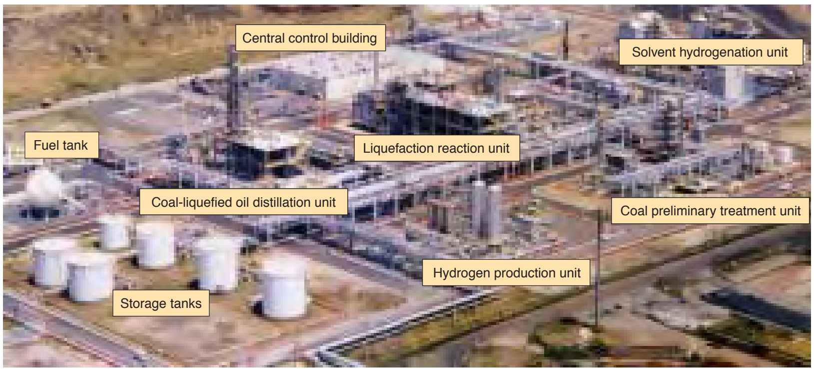


Fig. 3 NEDOL Process pilot plant (150 t/d)

References

1) Sadao Wasaka: "Bulletin of The Japan Institute of Energy," 78 (798), 1999.
2) "Development of Coal Liquefaction Technology - A Bridge for Commercialization," Nippon Coal Oil Co., Ltd.
3) Haruhiko Yoshida: "Coal Liquefaction Pilot Plant," New Energy and Industrial Technology Development Organization.

4A3. Brown Coal Liquefaction Technology (BCL)

Research and development: New Energy and Industrial Technology Development Organization; Kobe Steel, Ltd.; Nissho Iwai Corp.; Mitsubishi Chemical Corp.; Cosmo Oil Co., Ltd.; Idemitsu Kosan Co., Ltd.; and Nippon Brown Coal Liquefaction Co., Ltd.
Project type: Development of Brown Coal Liquefaction Technology; Development of Basic Liquefaction Technology; Coal Liquefaction International Cooperation Project; and other projects
Period: 1981-2002 (21 years)

Technology overview

1. Background and process overview

Economically recoverable coal reserves are expected to total about one trillion tons, about one-half of which are comprised of low-rank coal such as sub-bituminous coal and brown coal. Coal has a larger ratio of reserves to production (R/P) than that of oil and natural gas. For the effective utilization of coal, however, the effective use of low-rank coal is essential. Low-rank coal contains a large amount of water, but unlike bituminous coal and other higher rank coals, has an autoignition property in a dry state. Consequently, brown coal liquefaction technology development has progressed with the aim to use it to contribute to a stable supply of energy in Japan by converting the difficult-to-use low-rank coal into an easy-to-handle and useful product, or by using it to produce clean transportation fuels such as gasoline and diesel oil.

As shown in Figure 1, the BCL process has four stages: the slurry dewatering stage, where water is efficiently removed from low-rank coal; the liquefaction stage, where liquefied oil production yield is increased by using a highly active limonite catalyst and bottom recycling technology; the in-line hydrotreatment stage where the heteroatoms (sulfur-containing compounds, nitrogen-containing compounds, etc.) in the coal-liquefied oil are removed to obtain high quality gasoline, diesel oil, and other light fractions; and the solvent de-ashing stage where the ash in coal and the added catalysts are efficiently discharged from the process. In Asian countries, economic growth has steadily increased energy demand, and countries possessing low-rank coal resources, such as Indonesia, anticipate commercialization of the technology.

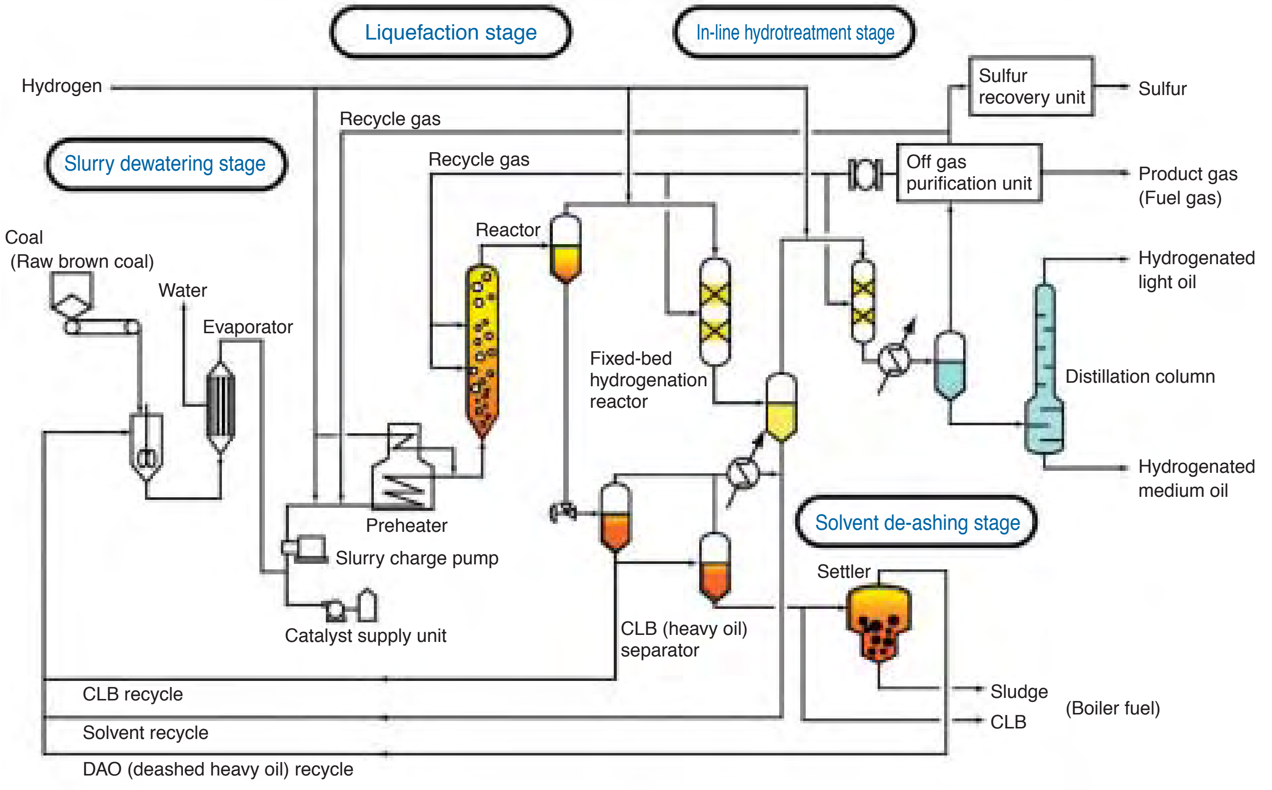


Fig. 1 Flowchart of BCL process

2. Development objectives and developed technology


Photo 1 Fifty t/d Pilot plant (Australia)

A pilot plant (Photo 1) study conducted under the governmental cooperation of Japan and Australia set the following technical targets:

(1) High liquefied oil production yield: 50% or greater

(2) Long-term continuous operation: 1,000 hours or greater

(3) High deashing performance: 1,000 ppm or less

(4) Establishment of new slurry dewatering process. Through four years of operation and study (1987- 1990), all of the above targets were achieved. Furthermore, scale-up data necessary to construct commercial liquefaction plants and expertise on plant operation were obtained through pilot plant operation. During the study period, (the 1990s), however, oil prices were low and supplies were stable worldwide. Thus, further improvements in the economics of the coal liquefaction process were vequired and cleaner liquefied oil was demanded owing to increased environmental concerns. Accordingly, a bench-scale plant (0.1 t/d) in Kobe Steel, Ltd.'s Takasago Works was constructed to conduct a study for improving the process. Results of the study included the development of: a limonite catalyst, an extremely active catalyst compared to existing liquefaction catalysts, and one possessing superior handling properties, such as excellent crushing characteristics; a method to maintain catalytic activity through bottom recycling technology; an in-line hydrotreatment technology that significantly improves the quality of coal-liquefied oil; and various improvements for increasing operational reliability. Through the development work, an improved BCL process (Improved Brown Coal Liquefaction Process: refer to the flowchart on the preceding page) that significantly improves the economics, reliability, and environmental compatibility of the brown coal liquefaction process was established.

3. Progress and development results

On the basis of a memorandum of understanding on cooperative coal liquefaction research between the Agency for the Assessment and Application of Technology of Indonesia and the New Energy and Industrial Technology Development Organization, a study team carried out surveys and liquefaction tests of low-rank coal in Indonesia beginning in 1994, in addition to screening candidate coals for liquefaction. Furthermore, the team endeavored to increase the technical abilities of the Indonesian engineers through technical training and the supply of liquefaction testing equipment. In 1999, the study team selected three candidate sites for a liquefaction plant in Indonesia, and carried out a feasibility study on coal liquefaction, including an economic evaluation. The feasibility study revealed that coal liquefaction would be economically feasible at a given oil price.

4. Issues and feasibility of practical application

Due to steady economic growth, energy demand in Asian countries is rapidly increasing. Since the stable supply of energy from Asian countries to Japan significantly contributes to the energy security of Japan, brown coal liquefaction technology that utilizes low-rank coal will play an important role.

References

1) Shunichi Yanai and Takuo Shigehisa: CCT Journal, Vol. 7, p. 29, 2003.

2) Report of the Results of the International Coal Liquefaction Cooperation Project, Cooperative Study of Development of Low Grade Coal Liquefaction Technology, 2003.

4A4. Dimethyl Ether Production Technology (DME)

Research and development: DME Development Co., Ltd., JFE Holdings Co., Ltd., Taiyo Nippon Sanso Corporation, Toyota Tsusho Corp., Hitachi Ltd., Marubeni Corp., Idemitsu Kosan Co., Ltd., INPEX Corporation, TOTAL S.A. (France), LNG Japan Co., Ltd., and Japan Petroleum Exploration Co., Ltd. (JAPEX).

Project type: National Grant project of "Development of Technology for Environmental Load Reducing Fuel Conversion" of the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry

Period: 2002-2006 (5 years)

Technology overview

1. Background and process overview

Dimethyl ether (DME) is a clean energy source and as it generates no sulfur oxide or soot during combustion its environmental impact is low. Owing to its non-toxicity and easy liquefaction properties, DME is easy to handle and therefore can be used as a domestic-sector fuel (substitute for LPG), transportation fuel (diesel vehicles, fuel cell vehicles), power plant fuel (thermal plants, cogeneration plants, stationary fuel cells), and as a raw material for chemical products. Currently DME is produced by dehydrating methanol. Approximately ten thousand tons per year are produced in Japan, and 150 thousand tons per year worldwide. DME's main use is as a spray propellant. Given the above-described superior properties, if DME were to become widely available in large volumes at a reasonable price, DME could be used as a fuel in a wide variety of fields.

2. Development objectives and technology to be developed

The objective of this study is the development of a process to directly synthesize DME from syngas (mixture of H_2 and CO), (Chemical reaction (1)).

Existing technology produces DME through the dehydration of methanol, (Chemical reaction (3)). The scale of the plant in actual operation, however, is rather small, and scaling-up is an issue to produce DME as a commercial fuel. In addition, the equilibrium conversion of the methanol synthesis reaction (Chemical reaction (2)) is relatively small, as show in Figure 1. On the other hand, because the methanol synthesis equilibrium limitation can be avoided in the direct DME synthesis reaction (1), a higher conversion rate can be achieved.

The reaction formulae relating to the direct synthesis of DME are provided below. The equilibrium conversions for methanol synthesis and direct DME synthesis are given in Figure 1. Since direct synthesis produces the maximum conversion with a syngas composition of $H_2/CO=1$, the process is suitable for the syngas produced from coal gasification ($H_2/CO=0.5\text{-}1$). The targets of the development study include the following:

1. DME production rate: 100 tons/day or greater, syngas total conversion: 95% or greater, DME selectivity: 90% or greater, DME purity: 99% or greater
2. Establishing scale-up technology
3. Optimizing entire system
4. Establishing stable plant operation

Chemical reaction:

(1) $3CO+3H_2 \rightarrow CH_3OCH_3+CO_2$

(2) $CO+2H_2 \rightarrow CH_3OH$

(3) $2CH_3OH \rightarrow CH_3OCH_3+H_2O$

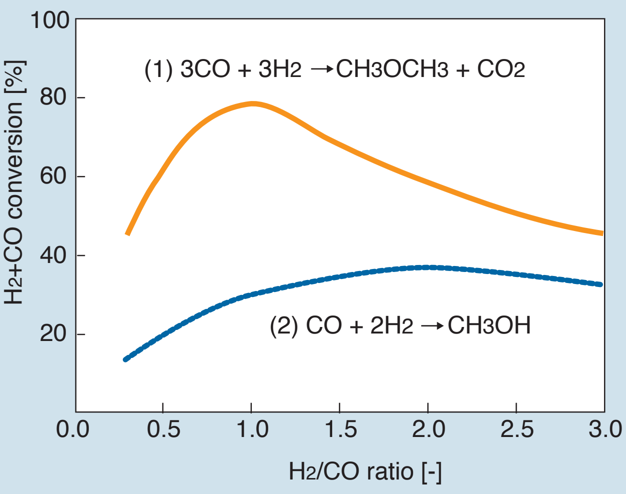


Fig. 1 Equilibrium conversion (280°C, 5Mpa)

3. Progress and development results

The development of the direct synthesis process has been led by JFE. The first step was the search for a direct synthesis catalyst. The second step was a small bench plant (5 kg/day). The third step was a 5 ton/day pilot plant (Photo 1) constructed with the aid of the Ministry of Economy, Trade and Industry (METI). The fourth step was a 100 ton/day demonstration plant (Photo 2) also constructed with the aid of METI. This demonstration plant was completed in November 2003 and is scheduled to have six long-term continuous operation runs over 2 to 5 months from the end of 2003 to 2006. The total production of the demonstration plant has reached approximately 19,000 tons.

Photo 1 Five ton/day pilot plant

Photo 2 One-hundred ton/day demonstration plant

4. Issues and feasibility of practical application

DME is already utilized as a fuel on a small-scale in an inland area of China. In Japan, activities toward the practical application of DME as a fuel are being undertaken by: DME International Co., Ltd., which was established by the same ten companies that established the DME Development Co., Ltd., aiming to study the commercialization of DME; Japan DME Co., Ltd., which was established by Mitsubishi Gas Chemical Co., Inc., Mitsubishi Heavy Industries, Ltd., JGC, and Itochu Corp.; and Mitsui & Co., Ltd. and Toyo Engineering Corp., which adopted the methanol dehydration process. These activities aim to supply DME product in 2006. All of them plan to use natural gas as the feedstock, because natural gas requires only a small initial investment. In the future, however, they are expected to switch to coal, which has larger reserves than natural gas, as the feedstock. Using natural gas, the CO_2 obtained from the CO_2 separation column is returned to the syngas generation furnace; if coal were to be used, however, the CO_2 would be released into the atmosphere. When long-term CO_2 storage technology is established in the future, the coal-based process will be able to provide purified CO_2 without any additional equipment. In the West, DME has drawn attention in a wide range of fields as a new fuel. There, however, it is expected to be mainly used in diesel vehicles to fully leverage the fact that DME combustion generates no soot.

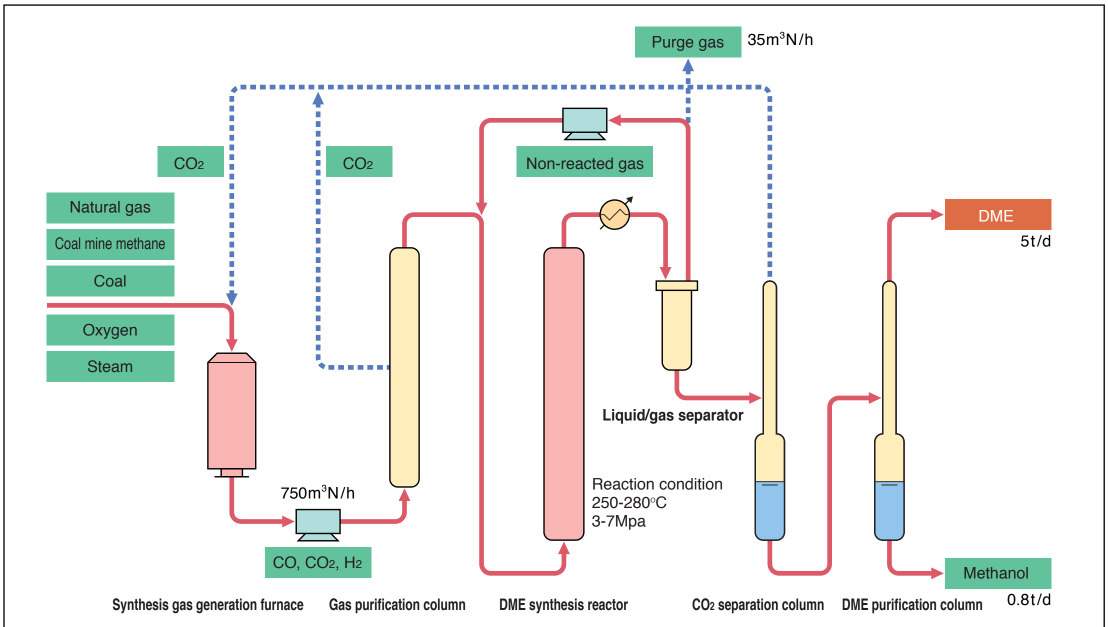


Fig. 2 Typical process flow diagram of DME direct synthesis from a coal or natural gas plant

References

1) Tsunao Kamijo et al., Lecture papers of The 8th Coal Utilization Technology Congress, Tokyo, pp.194-205, 1998.
2) Yotaro Ohno et al., Preprint for the lectures of the 30th Petroleum and Petrochemical Discussion Meeting, Tokyo, pp. 26-29, 2000.
3) Yotaro Ohno: Japan DME Forum Workshop, Tokyo, pp.113-122, 2002.

4B1. Multi-purpose Coal Conversion Technology (CPX*)

Research and development: Japan Coal Energy Center; Nippon Steel Engineering Co., Ltd.; JFE Steel Corp.; Sumitomo Metal Industries, Ltd.; Kobe Steel Ltd.; Ube Industries, Ltd.; Idemitsu Kosan Co., Ltd.; Nippon Steel Chemical Co., Ltd.
Project type: Subsidized coal production/utilization technology promotion
Period: 1996-2000 (5 years)

*Coal Flash Pyrolysis Process: CPX stands for Coal Pyrolysis suffixed with X, indicating diverse products.

Technology overview

1. Technological features

In an attempt to further expand coal's versatile uses, the aim of this project was to develop multi-purpose coal conversion technology with excellent efficiency, economic feasibility, and environmental-friendliness, mainly for the purpose of manufacturing medium-calorie gas as industrial fuel and liquid products as feedstocks for chemicals.

The technological objectives were as follows:

1. Moderate operational conditions

- A pyrolysis reactor operating at temperatures as low as 600-950°C.

- A reaction pressure of less than 1Mpa, much lower than several to tens of Mpa used in the coal liquefaction and hydro-gasification processes.

2. High overall thermal efficiency

- Flash pyrolysis of coal combined with a partial recycling of generated char to gasify more char, thereby improving thermal efficiency of the process.

3. Multiple varieties of coal

- Utilizing lower grades of coal, from sub-bituminous to highly volatile bituminous coal, as primary material to enable high gas/tar yields.

4. Efficient separation of coal ash

- Coal ash discharged from gasifier as molten slag and then granulated with water.

5. Diversified utilization of available products

- Among products, gas can be used as industrial fuel, liquids (light oil/tar) as feedstocks for chemicals, solid char as fuel or a reducer, and slag as a raw material for cement.

- Heating value of gas produced from the process to approach approximately 3,500kcal/Nm^3.

- Combined yield of gas and liquid (light oil/tar) 70% or more of coal input.

6. Controllable yield of products

- A change in pyrolysis temperature (600-950°C) or type of coal allows product yields to be adjusted accordingly.

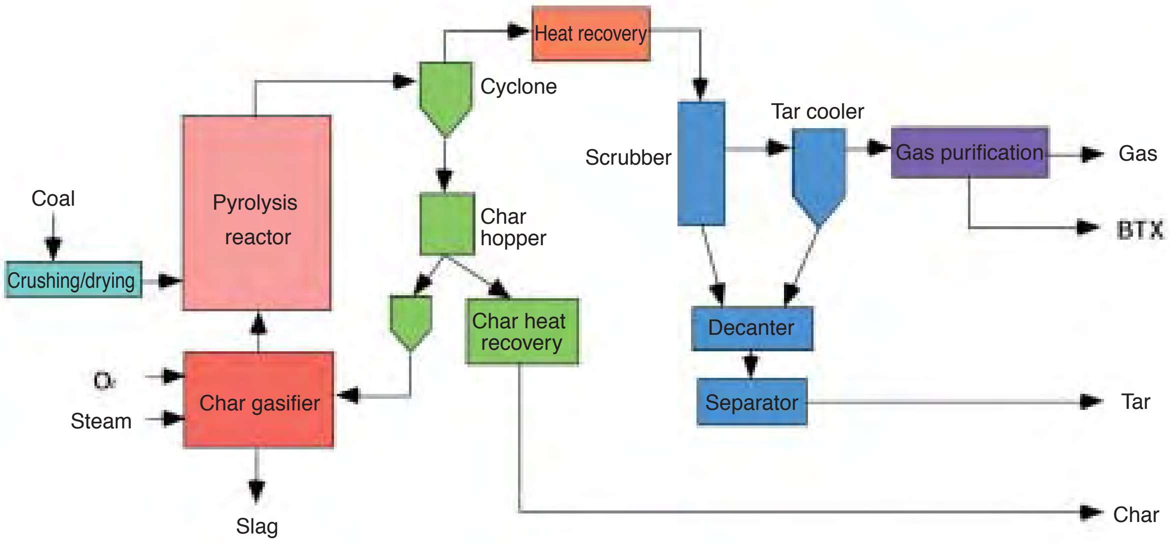


Fig. 1 Process flow diagram

2. Summary of technology

This conversion process is characterized by higher overall thermal efficiency, achieved with a compact, low-pressure char/oxygen gasification system that combines the flash pyrolysis of coal and the partial recycling of pyrolyzed char to use the sensible heat of the char gasification gas as a heat source for the flash heating/pyrolysis reaction of pulverized coal (Fig. 1). The entrained-bed coal flash pyrolysis process has been developed to not only produce more high-value-added gas and liquid (tar and oil) with a coke oven gas (COG)-equivalent heating value, but also supplies the heat necessary for pyrolysis. Pulverized and dried coal (of about 50 μm in grain size) is injected into the pyrolysis reactor and mixed with 600-950°C gas and several atm. In a reaction lasting two seconds, the coal is flash heated/pyrolyzed. Part of the pyrolyzed solid char is recycled to the hot gas generation section (char gasifier) to be partially oxidized by oxygen and steam, thus allowing an approximately 1,500-1,600°C gas stream, mainly composed of CO and H_2, to be generated so that the sensible heat of the gas can be used to supply heat for the pyrolysis reaction. The pyrolysis reactor employs an up-flow system where the hot gas generated at this gasifier is fed from the lower part of the reactor and, after pyrolyzed coal is mixed, leaves the system at the reactor's upper part together with pyrolyzed products. A portion of the solid product (char) separated at the cyclone is recycled to the char gasifier and the remainder is offered as a product after heat recovery. Heat is recovered from the gas containing pyrolyzed products until it cools down to approximately 350°C through an indirect heat exchange with thermal oil while tar passes the venture scrubber/tar cooler to be recovered. Pyrolysis gas is made available for use as industrial-purpose fuel gas after purification, such as through light oil (BTX) recovery and desulfurization. At the pilot plant (Photo 1), built within the Yawata Works of Nippon Steel Corp., tests were conducted mainly with a view to the evaluation/verification of process component/total system technologies to establish the technological basis for commercialization as well as to obtain data that would aid in the design of an actual plant (1,000t/d) and to evaluate its economic feasibility. In a period of two years, beginning in 1999, it was test-run ten times in all, achieving a maximum 210 hours of stable, continuous operation. During this period, the aforementioned features were verified, assuring the controllability of products at certain pyrolysis temperatures (Fig. 2) prior to completing the data collection process.

Photo 1 Pilot plant

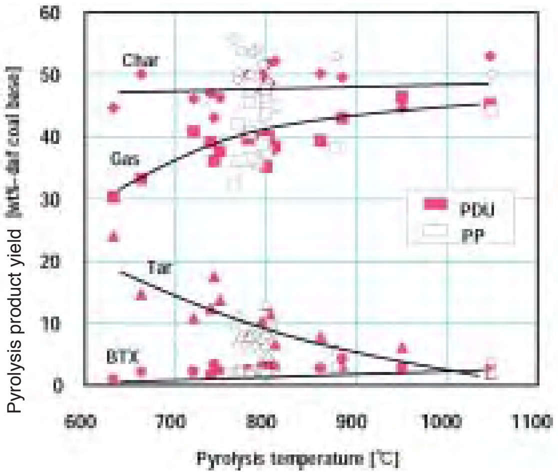


Fig. 2 Relationship between pyrolysis product yield and pyrolysis temperature
PDU: 7 ton/day test equipment

References

1) Hiroyuki Kozuru et al., Advanced Clean Coal Technology Int'l Symposium, 2001.
2) Masami Onoda et al., 10th Annual Conference on Clean Coal Technology abstracts, 2000.
3) Shigeru Hashimoto et al., Pittsburgh Coal Conference, 2000.

4B2. Efficient Co-production with Coal Flash Partial Hydropyrolysis Technology (ECOPRO)

Research and development: Japan Coal Energy Center; New Energy and Industrial Technology Development Organization; National Institute of Advanced Industrial Science and Technology; Nippon Steel Engineering Co.,Ltd.; Babcock Hitachi K.K.; Mitsubishi Chemical Corporation
Project type: Subsidized coal production/utilization technology promotion project
Period: 1. Coal utilization next-generation technology development survey, 1996-1999 (4 years)
2. Coal utilization commercialization technology development, 2003-2008 (6 years)

Technology overview

1. Technological objective

Clean coal technology-related development solely focused on a single industry in pursuit of a single product is reaching its limits in terms of efficiency and economy. This is necessitating the development of innovative technologies that could completely revolutionize energy and material production.

Efficient Co-production with Coal Flash Partial Hydropyrolysis Technology (ECOPRO) is a technology that causes pulverized coal to react rapidly under high pressure (2-3MPa) and in a moderate hydrogen atmosphere to highly efficiently obtain, from one reactor, synthetic gas that can easily be converted for use such as in integrated gasification combined-cycle (IGCC) power generation, indirect liquefaction (GTL), and chemicals, while co-producing light oil for utilization as a feedstock for chemicals and fuel.

The realization of a coal-based cross-industrial composite project, led by the electric power, chemical, and steel industries, with this technology as its core will hopefully bring a dramatic improvement to total energy utilization efficiency.

2. Technology overview

Figure 1 shows the total process flow of this technology. At the partial oxidation section of a coal flash partial hydropyrolsyis reactor, pulverized coal and recycled char are gasified with oxygen and steam at a pressure of 2-3MPa and at a temperature of 1,500- 1,600°C to give hot gas mainly composed of CO and H_2. At the reforming section directly connected through a throat to the partial oxidation section, pulverized coal is injected together with recycled H_2 into the hot gas stream from the partial oxidation section to complete the reforming reaction (partial hydropyrolysis) instantly under the condition of 2-3MPa in pressure, 700-900°C in temperature, and approximately 30-50% in hydrogen concentration (H_2 in hot gas and recycle H_2 combined). At that time, hot gas from the partial oxidation section also functions as a source of the reaction heat required at the reforming section. At the reforming section, a hydrogenation reaction adds H2 to primary pyrolysis, such as tar released from pulverized coal, changing heavy tar-like matter to light oil. The gas, light oil, and char produced at the partial hydropyrolysis reactor follow a process where, after char separation at the cyclone and subsequent sensible heat recovery, synthetic gas (syngas) should be formed by way of oil recovery, desulfurization, and other gas purification processes. A portion of the syngas is

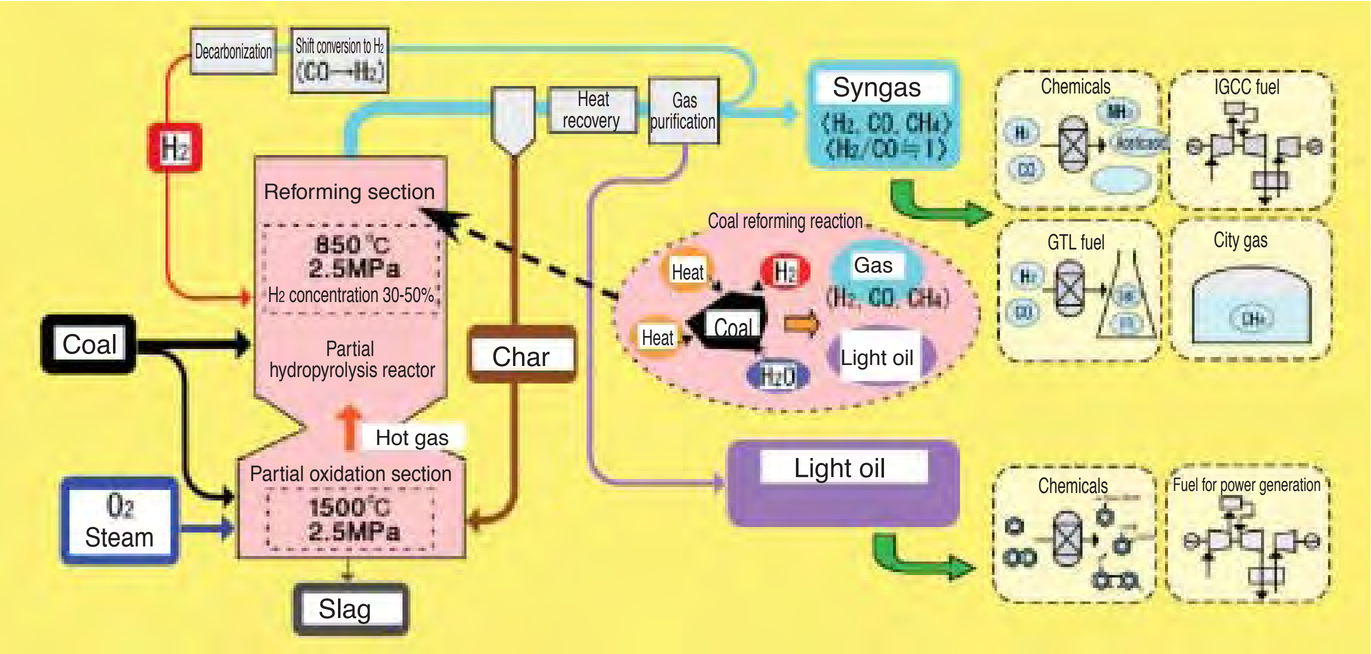


Fig. 1 Process flow chart

converted into H_2-rich gas, in the course of a shift reaction and decarbonization (CO_2 recovery). After pre-heated via a heat exchange, the gas is recycled to the partial hydropyrolysis reactor's reforming section. The final syngas product is characterized by its main composition of H_2, CO, and CH_4 as well as hydrogen-rich contents of H_2/CO≒1 and is used as a source gas for IGCC, GTL, and chemicals. Light oil is mainly composed of aromatic compounds with 1-2 rings such as benzene and naphthalene, which have applications for chemical manufacturing or fuel for power generation.

The features of this technology include:

1. High-efficiency: The sensible heat of hot gas generated at the partial oxidation section is effectively used as a source of heat required at the reforming section, providing high energy conversion efficiency.
2. Flexible productivity: The reforming section temperature, as well as the amount of hydrogen injected, can be controlled, allowing the freedom to change the gas/oil composition and output ratio, thereby flexibly responding to consumers' needs.
3. Economy: The cost of producing syngas can be partially offset by the value of the of co-produced high-value-added oil.

3. Progress and development results

1) Basic partial hydropyrolysis test (1996-1999, 1kg/day)

Using a small-scale test unit, the pyrolysis behavior of coal under the target conditions of this technology was reviewed, confirming that the hydropyrolysis of the primary tar released from the flash heating/pyrolysis reaction of coal was successful.

2) Process development unit (PDU) test (2000-2003, 1t/day Nippon Steel Engineering Co., Ltd. in-house research)

Using a reforming/partial oxidation-integrated PDU test unit, the basic performance of a partial hydropyrolysis reactor as the core of this technology was evaluated, clarifying the reaction in the reactor.

3) Pilot plant test (2003-2008, 20t/day)

Tests are being conducted using a pilot plant with a thermally self-supportable reactor combined with other ancillary process units to enable forecasts for a future demonstration unit (up to 1,000t/day).

Table 1 Development subjects for pilot plant tests

Technology to be developed	R&D topics
Verification of the reaction in the partial hydropyrolysis reactor/ establishment of reactor control technology	- Quantification of partial hydropyrolysis reactor reaction - Establishment of reactor conditions for optimum transition zone formation - Establishment of high-efficiency gasification (partial oxidation section) operational conditions
Development of process/factor technologies	- Establishment of technology to separate/recover char from gas - Establishment of technology to recover heat from gas co-existent with oil
Total system evaluation, etc.	- Establishment of extended continuous operation technology - Establishment of scale-up approach for demonstration unit design

Table 2 Development timetable

	2003	2004	2005	2006	2007	2008
Pilot plant test						
Design/production/construction work	🟩	🟩	🟩	🟩		
Testing studies				🟩	🟩	🟩
Disassembly studies						🟩
Supporting studies	🟩	🟩	🟩	🟩	🟩	🟩

References

1) H. Shimoda et al., 10th Annual Conference on Clean Coal Technology lecture collection, p. 296, 2000.
2) H. Yabe et al., 2nd Japan-Australia Coal Research Workshop Proceedings, p. 257, 2002.

4C1. Coal Cartridge System (CCS)

Technology overview

1. System overview

The Coal Cartridge System (CCS) collectively imports and blends imported coal on behalf of medium-/small-lot consumers who use several thousand tons of coal per year, but for whom it is difficult to directly import. Through CCS, the imported coal is blended into suitable qualities and supplied to consumers as pulverized coal. This system was subjected, under a 3-year program starting in 1985, to demonstration tests at manufacture/supply and combustion bases, in an attempt to establish the reliability of CCS in regards to coal blending and meeting the consumers' quality requirements. As a result, the first Japanese CCS center, with a capacity to produce 200 thousand tons per year, was built in 1991 and operation of two CCS coal-dedicated boilers commenced.

2. Features

In a typical pulverized coal-fired system, before the coal is combusted, it is stored in a stockyard. Next, it is pulverized in a mill prior to being fed to a boiler. In CCS, however, the coal is pulverized at a production/supply facility, and all processes are completed within a sealed environment, from loading the coal onto tank lorries to delivery and unloading into consumers' coal silos after which it is then supplied to boilers. This environment-friendly process not only eliminates the problem of the dispersion of coal dust, but also enables smoother operation through easier control of powder flows and, therefore, fluctuations in boiler loads. CCS provides several benefits to consumers, like negating the need for a mill or a coal yard since the coal can now be stored in a silo. It also reduces capital investments because of the compact equipment configuration, thus leading to labor savings, as well as a better environment. CCS is, as mentioned above, a pulverized coal utilization system featuring improved coal handling and a sealed-carriage system.

3. Technical data

General attributes of CCS coal are shown in Table 1.

Table 1 General attributes of CCS coal

Brand		Referential control	A	B	C
Raw coal for mixture			3 kinds	3 kinds	2 kinds
Total moisture Wt%		AR	2.9	2.8	2.7
Heating value kcal/kg		*	6490	6480	6490
Ultimate analysis	Moisture Wt%	dry	0.0	0.0	0.0
	Ash Wt%	dry	12.1	12.4	12.1
	Volatiles Wt%	dry	39.6	39.5	35.6
	Fixed carbon Wt%	dry	48.3	48.1	50.3
Fuel ratio			1.22	1.22	1.41
Proximate analysis	Carbon Wt%	daf	80.30	80.00	82.00
	Hydrogen Wt%	daf	5.80	5.80	5.90
	Nitrogen Wt%	daf	1.60	1.50	1.50
	Oxygen Wt%	daf	11.80	12.40	10.50
	Sulfur Wt%	daf	0.48	0.47	0.45
Total sulfur Wt%		dry	0.45	0.43	0.41
Grain size -200 mesh		dry	84.5	78.9	83.50

4. Process flow

Figure 1 shows a process flow diagram and system overview of a CCS coal production/supply facility.

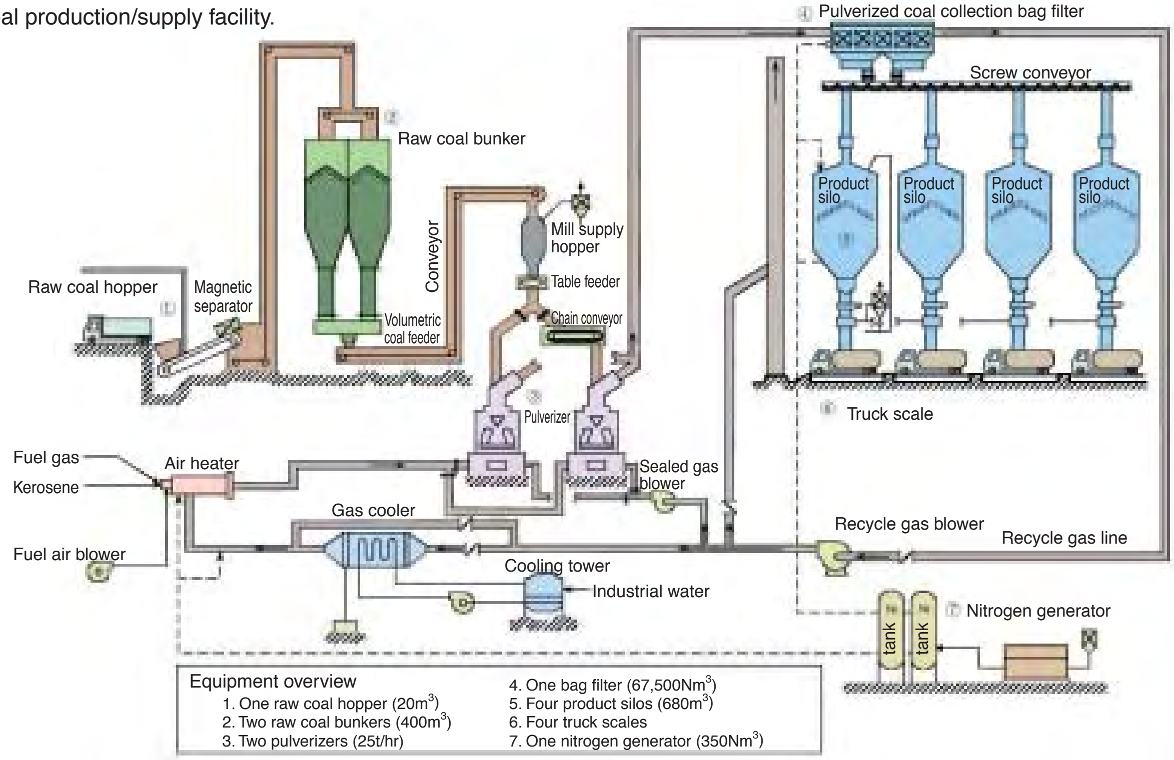


Fig. 1 Process flow of CCS coal production/supply facility

4C2. Coal Water Mixture Production Technology (CWM)

Technology overview

1. Coal slurry overview

The fact that coal is a solid causes some challenges; it requires more complex handling than a fluid does, environmental measures must be undertaken to prevent the dispersion of its dust, and a lot of space is required to store it. Utilizing it in a slurry form offers the potential to make the use of coal cleaner, comparable to heavy oil. One type of coal slurry, coal oil mixture (COM), is prepared by adding heavy oil to coal. This is different than another slurry, coal water mixture (CWM), a mixture of coal and water. While COM is convenient for burning and while it was tested before CWM, it failed to catch on because of the demand for heavy oil for other uses. CWM, on the other hand, poses no problems relative to spontaneous combustion or dust dispersion and can be handled as an easy-to-treat liquid. Conventional coal slurry, without additives could be piped but, due to an approximate 50% water content, exhibited poor long-run stability, and required dehydration before firing. High-concentration CWM can now, as a result of studies on the particle size distribution of coal and the development of a dispersant and other additives, be kept fluid as well as stable even when less water is added, allowing it to be directly combusted without being de-watered. The inclusion of only a small amount of additives stabilizes the coal-water slurry in which coal particles of a certain size distribution are uniformly dispersed, constituting a weight concentration of approximately 70%.

2. Characteristics of high-concentration CWM

The typical characteristics of high-concentration CWM (Chinese coal CWM) are shown in Table 1 below.

Table 1 Characteristics of high-concentration CWM

Coal concentration (wt%)	68-70
Higher heating value (kcal/kg)	5,000-5,200
Lower heating value (kcal/kg)	4,600-4,800
Apparent consistency (mPa-s)	1,000
Specific gravity (-)	1.25
Ash content (wt%)	6.0
Sulfur content (wt%)	0.2
Grains of 200 mesh or less (%)	80-85

1) Coal type

In general, high-carbonization, low-inherent moisture (about 5% or less in approximate analysis), and low-oxygen content (about 8% or less in ultimate analysis) coal is suitable for high-concentration CWM.

2) Additives

Additives consist of dispersants and stabilizers. A dispersant functions to disperse coal particles into slurry, using electrostatic repulsion effects or steric repulsion effects; sodium sulfonate from naphthalene, polystyrene, polymethacrylate, polyolefine, and the like are used here. Additives, including the stabilizers CMC and xanthan gum, are used to prevent coal particles in the slurry from settling.

3) Particle size distribution

For higher concentration and stability CWM, the size of the pulverized coal should preferably be distributed over a wide range rather than narrowly distributed. Standard particle sizes used are roughly as shown in Table 2.

Table 2 Grain size distribution of high-concentration CWM

Maximum grain size	150-500 μm
Average grain size	10-20 μm
Grains of 74 μm or less	80% or more
Fine grains of several micrometers or less	Around 10%

4) Rheological characteristics

CWM's fluidity has characteristics of a non-Newtonian fluid but can be characterized as approaching a Bingham fluid. The fluidity characteristics also change, depending upon the type of coal, concentration, additives, and flow state. The apparent viscosity is roughly 1,000mPa-s (at room temperature and shear speed of 100/s).

5) Heating value

The heating value depends upon the type of coal used. An average lower heating value is 4,600-4,800kcal/kg.

3. Manufacturing process for high-concentration CWM

High-concentration CWM can be produced by pulverizng coal into a particle size distribution suitable for CWM, selecting the correct additives (a dispersant and a stabilizer), and appropriately blending the coal, water, and additives to manufacture a highly-concentrated, low-viscosity, highly-stable, and good-quality CWM. A diagram of the CWM manufacturing process is shown in Figure 1.

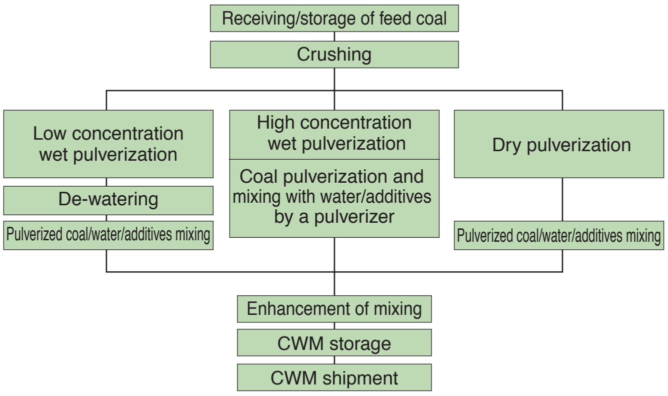


Fig. 1 CWM manufacturing process

Coal water mixture (CWM)

4C3. Briquette Production Technology

Technology Overview

1. Background

Global warming, caused by CO_2 and other substances, has become an international concern in recent years. To protect forestry resources, which act as major absorbers of CO_2, controlling the ever-increasing deforestation, along with the increase in the consumption of wood fuels, such as firewood and charcoal, is an urgent issue. Given this, the development of a substitute fuel for charcoal is necessary. Briquette production technology, a type of clean coal technology, can help prevent flooding and serve as a global warming countermeasure by conserving forestry resources through the provision of a stable supply of briquettes as a substitute for charcoal and firewood.

2. Carbonized briquettes

(1) Process overview

The coal briquette carbonization production process consists of a carbonization stage and a forming stage. Figure 1 shows the basic process flow.

In the carbonization stage, an internal-heating, low-temperature fluidized-bed carbonization furnace (approximately 450°C) produces smokeless semi-coke containing approximately 20% volatile matter. The carbonization furnace has a simple structure, with no perforated plates or agitator, making it easy to operate and maintain.

In the forming stage, the smokeless semi-coke and auxiliary raw materials, hydrated lime and clay, are thoroughly mixed at a predetermined mixing ratio. After pulverizing, the mixture is blended with a caking additive while water is added to adjust the water content of the mixture. The mixture is kneaded to uniformly distribute the caking additive, and to increase the viscosity in order to make the forming of the briquettes easy. The mixture is then introduced into the molding machine to prepare the briquettes. The briquettes are dried and cooled.

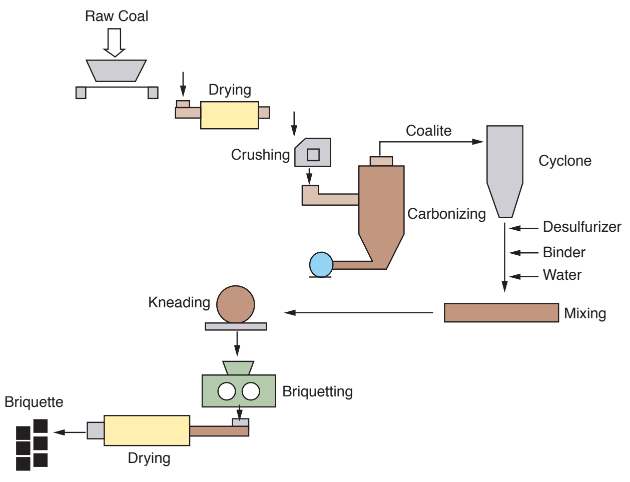


Fig. 1 Process flow of briquette production

(2) Carbonization stage

The raw coal (10% or lower surface water content, 5-50mm particle size) is preliminarily dried in a rotary dryer. The gas exhausted from the dryer passes through a multi-cyclone to remove the dust before venting the gas to the atmosphere. Figure 2 shows a cross-sectional view of the internal-heating, low-temperature fluidized-bed carbonization furnace, the most efficient process for carbonizing semi-coke and one which retains approximately 20% of the volatile matter in the semi-coke.

The preliminarily dried raw coal is charged to the middle section of the furnace, and is subjected to fluidization carbonization. The semi-coke is discharged from the top of the furnace together with the carbonization gas. The semi-coke is separated from the carbonization gas by the primary cyclone and the secondary cyclone.

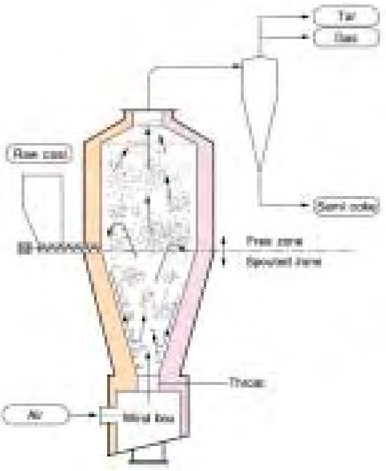


Fig. 2 Cross-sectional view of carbonization furnace

After cooled, the semi-coke is transferred to a stockyard, and the carbonization gas is supplied to the refractory-lined combustion furnace, where the carbonization gas is mixed with air to combust. The generated hot gas is injected into the raw coal dryer and to the succeeding briquette dryer to use as the drying heat source for the preliminary heating of the raw coal and the drying heat source of the formed oval briquettes.

(3) Forming stage

The semi-coke (Coalite) produced in the carbonization stage is the raw material for the briquette, containing adequate amounts of volatile matter, little ash and sulfur, and emitting no smoke or odor. The semi-coke, as the primary raw material, is mixed with hydrated lime (sulfur fixing agent), clay (to assist forming), and a caking additive.

To attain uniform composition and improved formability, the blended raw materials are fully kneaded. The forming of the mixture is carried out using a roll-molding machine at normal temperatures and under approximately 1,000 kg/cm (300-500 kg/cm^2) of line pressure. Photo 1 shows the forming state.

In the final stage, the formed briquettes are dried in the continuous dryer. Since semi-coke is used as a raw material for the briquettes, they are highly ignitable and can readily ignite in the furnace if the dryer is not operated at low temperatures. The dryer was designed with this temperature-sensitive concern in mind.

Photo 1 Formed briquettes

3. Bio-briquettes

Bio-briquettes are a type of solid fuel, prepared by blending coal with 10-25% biomass, such as wood, bagasse (fibrous reside of processed sugar cane stalks), straw, and corn stalks. A desulfurizing agent, $Ca(OH)_2$, is also added in an amount corresponding to the sulfur content of the coal. Owing to the high pressure briquetting (1-3 t/cm^2), the coal particles and the fibrous biomass material in the bio-briquette strongly intertwine and adhere to each other. As a result, they do not separate from each other during combustion, and the low ignition temperature biomass simultaneously combusts with the coal. The combined combustion gives favorable ignition and fuel properties, emits little dust and soot, and generates sandy combustion ash, leaving no clinker. Furthermore, since the desulfurizing agent also adheres to the coal particles, the agent effectively reacts with the sulfur in the coal to fix about 60-80% of the sulfur into the ash. Many coal ranks can be used, including bituminous coal, sub-bituminous coal, and brown coal. In particular, the bio-briquettes produced with low grade coal containing large amounts of ash and having low calorific value combust cleanly, thus the bio-briquette technology is an effective technology to produce clean fuel for household heaters and small industrial boilers.

(1) Bio-briquette production process

Figure 3 shows the basics of the bio-briquette production process. The raw materials, coal and biomass, are pulverized to a size of approximately 3 mm or smaller, and then dried. The dried mixture is further blended with a desulfurizing agent, $Ca(OH)_2$. The mixture is formed by compression molding in a high-pressure briquetting machine. Powder coal may be utilized without being pulverized. A small amount of binder may be added to some coal ranks. The production process does not involve high temperatures, and is centered on a dry, high-pressure briquetting machine. The process has a simple flow, which is safe and which does not require skilled operating technique. Owing to the high-pressure briquetting process, the coal particles and the biomass strongly intertwine and adhere to each other, thus the process produces rigid formed coal, which does not separate during combustion.

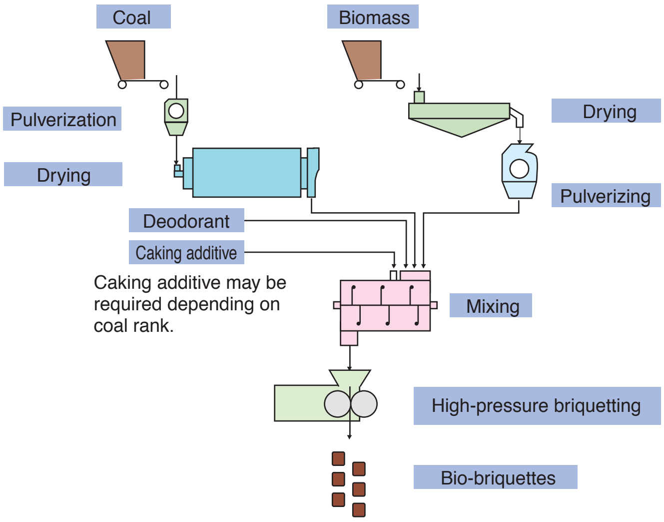
(2) Bio-briquette characteristics

1. Bio-briquette combustion decreases the generation of dust and soot to one-fifth to one-tenth that of direct coal combustion. Direct coal combustion increases the generation of dust and soot because the volatile matter released at low temperatures (200-400°C) does not completely combust. To the contrary, bio-briquettes simultaneously combust the low ignition point biomass, which permeates the coal particles, assuring the combustion of volatile matter at low combustion temperatures. As a result, the amount of generated dust and soot is significantly reduced.

2. Bio-briquettes prepared by blending biomass with coal have a significantly shorter ignition time. In addition, because of the low expansibility and caking property of bio-briquettes, sufficient air flow is maintained between the briquettes during continuous combustion such as in a fireplace. As a result, the bio-briquettes have superior combustion-sustaining properties, and do not die out in a fireplace or other heater even when the air supply is decreased. This makes it easy to adjust the combustion rate.

3. Since fibrous biomass is intertwined with the coal particles, there is no fear of the fused ash in the coal adhering and forming clinker-lumps during combustion. Instead, the ash falls in a sandy form through the grate. Therefore, aeration is maintained to stabilize the combustion state. Furthermore, since no clinker is formed, the ash contains very small amounts of unburned coal.

4. The bio-briquettes are formed under high compressive force. Because of this, the desulfurizing agent and the coal particles strongly adhere to each other, and they effectively react during combustion. With the addition of a desulfurizing agent at a ratio of approximately 1.2-2 of Ca/S, 60-80% of the sulfur in the coal is fixed in the ash.



Caking additive may be required depending on coal rank.

Fig. 3 Basic process flow for bio-briquette production

4C4. Coal and Woody Biomass Co-firing Technology

Research and development: New Energy and Industrial Technology Development Organization;
Chugoku Electric Power Co., Inc.; Hitachi, Ltd.; Babcock-Hitachi K.K.
Project type: High-efficiency biomass energy conversion technology development
Period: 2001-2003 (3 years)

Technology overview

1. Background

As part of their global warming countermeasures, industrially advanced countries are implementing policies to promote the adoption of power generation using renewable energy. One of these is the Renewable Portfolio Standard (RPS) system. The "Special Measures Law concerning the Use of New Energy by Electric Utilities" (RPS Law) was enacted in April 2003, and obligates electric utilities to obtain a specified amount of their energy from new energy power generation sources. The portion of energy derived from alternative sources is expected to increase from 3.3GkWh in 2003 to 12.2GkWh in 2010. Included in the definition of new energy is biomass fuel.

The co-firing of coal and woody biomass in the power generation sector, though already underway in the U.S. and European countries, is new to Japan and is facing a variety of technological problems. For pulverized coal-fired boilers, there are roughly two co-firing options. One is to simply pulverize the woody biomass in existing mills and combust the pulverized coal-biomass mixture fuel in a boiler, using the existing burner. This method requires fewer equipment modifications and therefore costs less. However, mixtures of more than several percent of biomass cause the mill's power consumption to sharply increase due to the difficulty of grinding woody biomass with ordinary pulverizers. The other option is to establish a biomass-dedicated mill. Despite the higher equipment costs, this method is advantageous not only because a higher ratio of biomass can be utilized but also because the amount of NOx generated can be reduced.

Technology development of the latter option, commissioned by the New Energy and Industrial Technology Development Organization (NEDO), is underway.

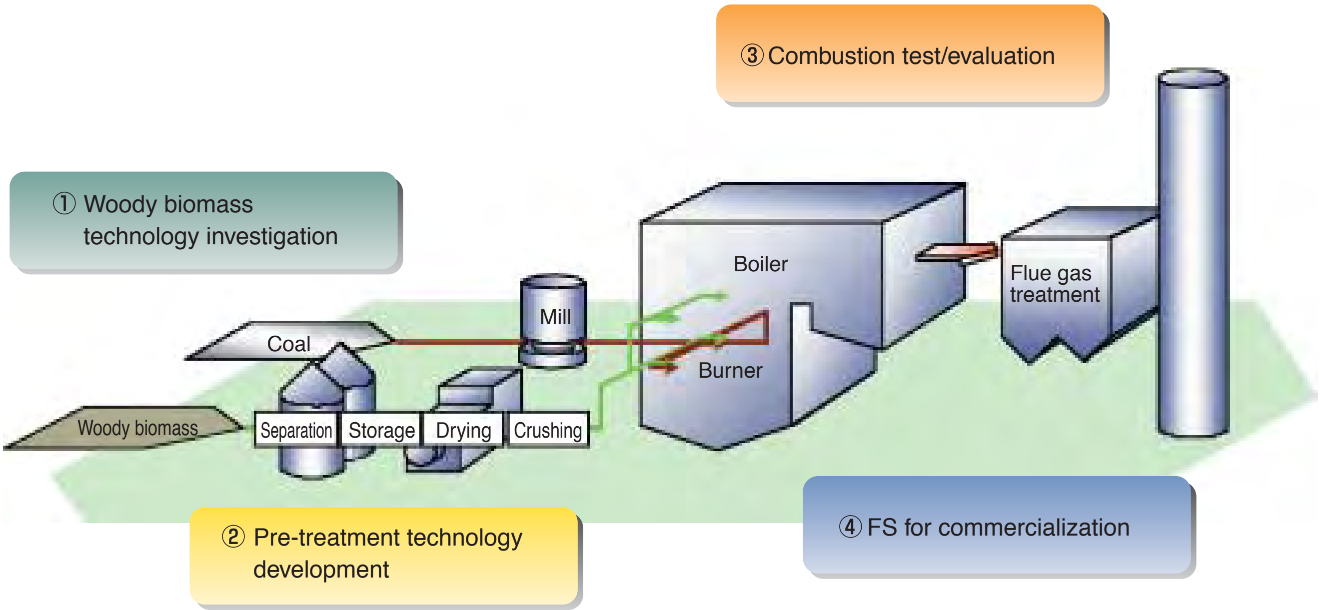


Fig. 1 Process flow of coal/woody biomass co-firing system

2. Development target

(1) Co-firing ratio of woody biomass: 5-10%

(2) Clearance of current regulatory environmental restrictions

(3) Power generation efficiency comparable to that of existing coal thermal power plants: A decrease in net thermal efficiency of less than 0.5% with a woody biomass co-firing ratio of 5% (on a calorific base).

3. Technologies to be developed

(1) Woody biomass pre-treatment technology (mainly grinding)

(2) Woody biomass combustion technology (co-firing burner/biomass-dedicated burner)

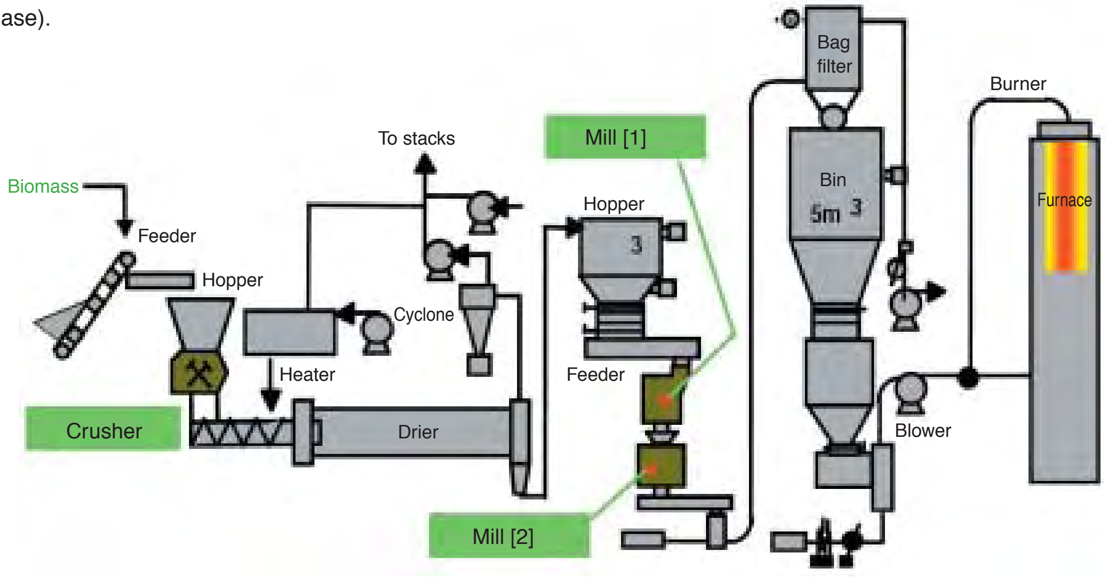
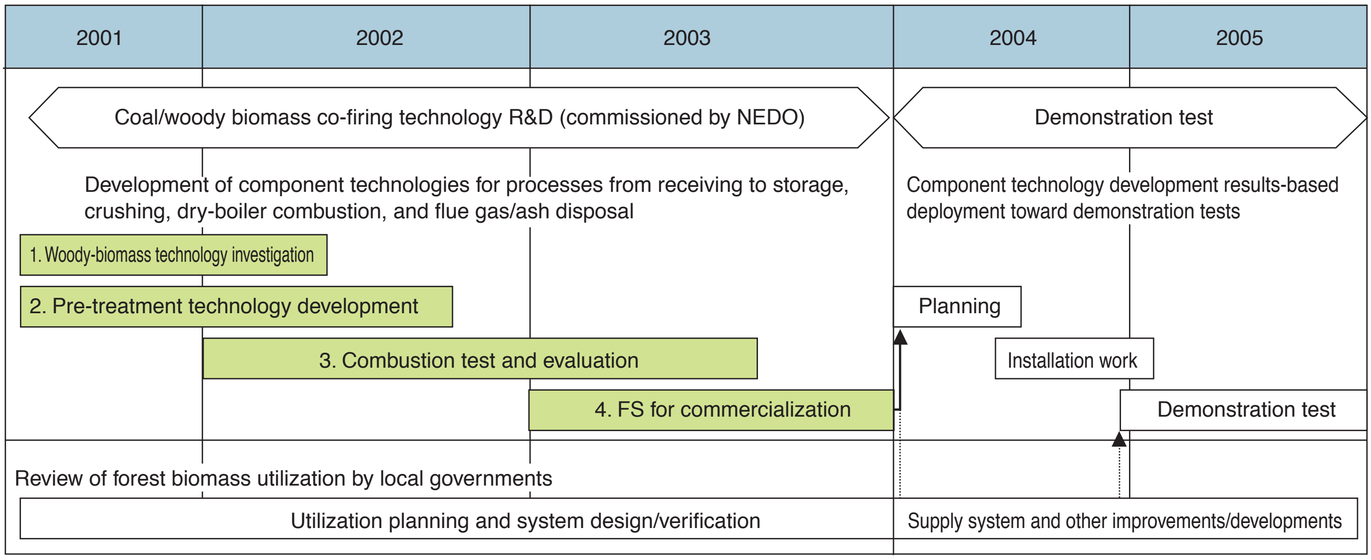


Fig. 2 Process flow of pilot-scale test facility

4. Development progress and results

This project, was conducted at Chugoku Electric Power Co., Inc., Hitachi, Ltd., and Babcock Hitachi K.K., and commissioned by NEDO, for the evaluation of the pilot plant's combustion results, with an eye toward commercialization.

R&D timetable



Development of component technologies for processes from receiving to storage, crushing, dry-boiler combustion, and flue gas/ash disposal

Component technology development results-based deployment toward demonstration tests

Review of forest biomass utilization by local governments

References

1) Kazuhiro Mae: Coal Utilization Technology Information Journal No. 253, pp. 3-5, Feb. 2002.
2) Hiroshi Yuasa: A collection of lectures from Thermal/Nuclear Power Generation Convention, Fukuoka, pp. 102-103, Oct. 2003.

4D1. Hyper-coal-based High-efficiency Combustion Technology (Hyper-coal)

Research and development: Japan Coal Energy Center; National Institute of Advanced Industrial Science and Technology; and Kobe Steel, Ltd.
Project type: Development and Survey of Next Generation Technology for Coal Utilization, promoted by New Energy and Industrial Technology Development Organization (NEDO)
Period: 2002-2007 (6 years)

Technology overview

1. Background and objectives

Because of abundant coal reserves, the expectations of a stable supply, and low cost, the demand for coal is expected to increase. The emission of CO_2 and other substances during the combustion of coal, however, has a more significant impact on the environment than does the use of other fossil fuels.

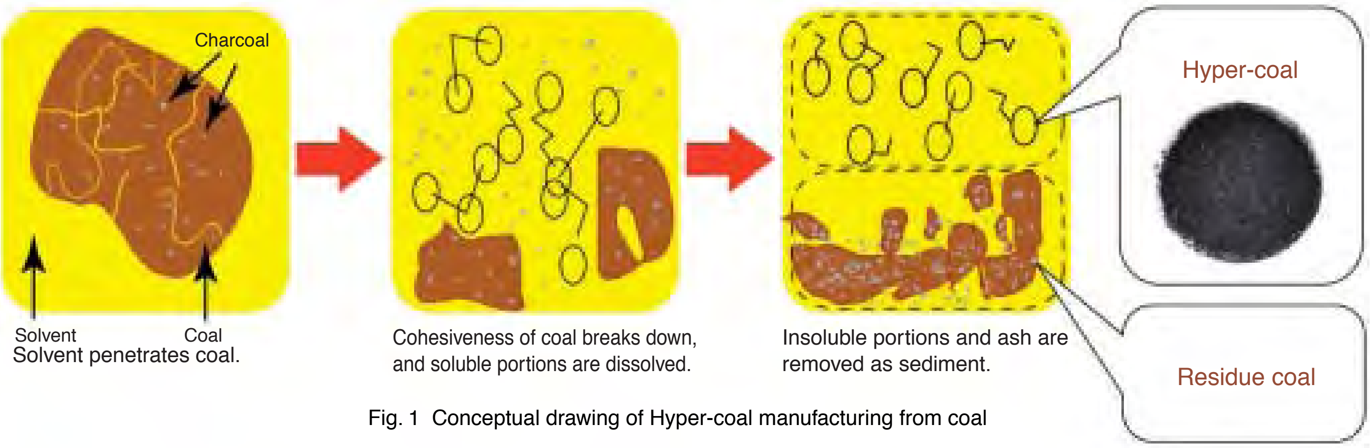
Given this, it is essential to decrease CO_2 emissions from coal-fired power plants, which account for a large percentage of the coal consumed. To do so, new power generation technology with higher thermal efficiency must be developed and disseminated worldwide.

If coal is directly utilized as a gas turbine fuel, the adoption of combined-cycle power generation systems (a combination of gas turbines and steam turbines) achieves more efficient power generation than existing pulverized coal-fired power generation. If impurities such as ash and alkali metals can be removed from coal, the clean coal can be used as fuel to be directly combusted in gas turbines.

NEDO is promoting the development of combined power generation technology, where coal treated by solvent extraction and ion exchange processes to remove the ash and alkali metals to obtain clean coal (Hyper-coal), can be directly combusted in gas turbines.

2. What is Hyper-coal?

A solvent with a high affinity to coal is applied during the ash extraction process. Ash present in the coal is removed from the solution though the use of a solid-liquid separation technology. Once the solvent is removed from the solution, the final product, Hyper-coal, has little ash content.



Solvent penetrates coal.

Cohesiveness of coal breaks down, and soluble portions are dissolved.

Insoluble portions and ash are removed as sediment.

Fig. 1 Conceptual drawing of Hyper-coal manufacturing from coal

3. Hyper-coal production facilities

(1) Heating-extraction unit

Coal is first treated with a solvent, and then the solution is treated by a high-temperature filtration process to remove residue, thus producing Hyper-coal. (Design temperature: 500°C, design pressure: 3MPa) This unit can produce various grades of Hyper-coal samples.

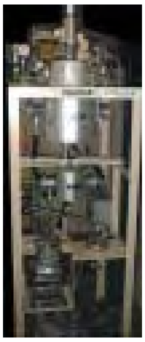


Photo 1 Heating-extraction unit

(2) Solid-liquid separation unit

Pictured in Photo 2 is a settler with the ability to separate coal from the sediment, (design temperature: 500°C, design pressure: 5 MPa). Five vertically arranged valves collect samples to determine the sedimenting state of un-dissolved matter under pressurized and heated conditions.

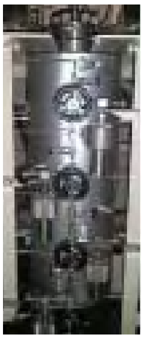


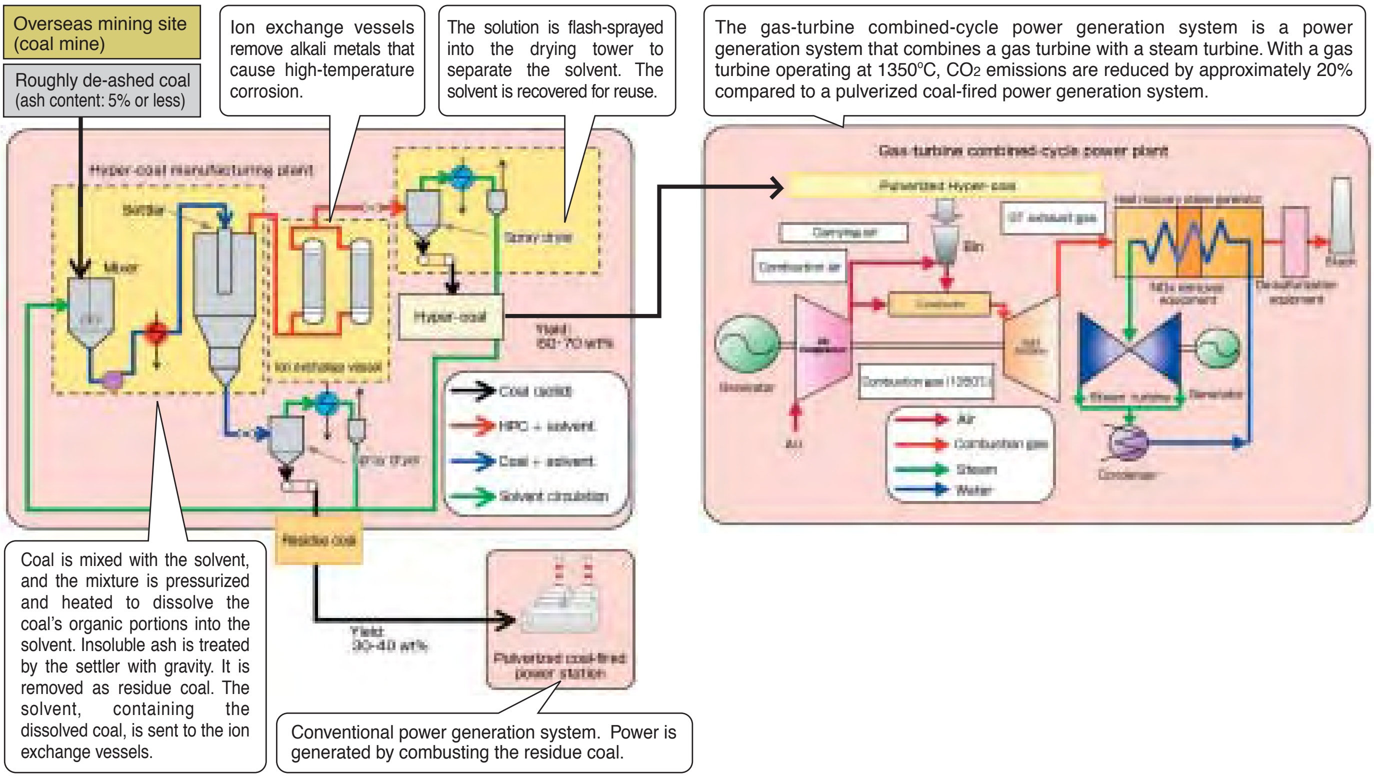
Photo 2 Solid-liquid separation unit

4. Features of Hyper-coal

- Ash content is decreased to 200 ppm or less. The concentration of alkali metals (Na, K) is decreased to 0.5 ppm or less by ion exchange.
- Calorific value increased by approximately 10-20% versus that of original coal.
- Inorganic sulfur is completely removed.
- Heavy metal content is significantly decreased to 1/100 or less.
- Residue coal, which amounts to 30-40% of original quantity of coal, can be used as steam coal.
- Low production costs: about $100/ton of Hyper-coal (HPC).
- HPC has excellent ignitability and combustion properties.
- HPC exhibits good thermal plasticity, and is a good carbon material for direct reduced iron and for smelting nonferrous metals.
- Since HPC is rich in volatile matter and is free from ash, it is an excellent gasification feedstock, and it is expected to improve the efficiency of gasification.

Photo 3 Test apparatus for continuous manufacturing of Hyper-coal

5. Configuration of Hyper-coal-based high-efficiency power generation system



Overseas mining site (coal mine)

Roughly de-ashed coal (ash content: 5% or less)

Ion exchange vessels remove alkali metals that cause high-temperature corrosion.

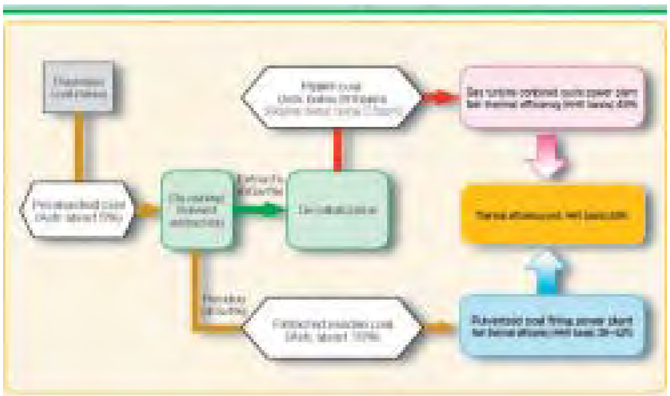
The solution is flash-sprayed into the drying tower to separate the solvent. The solvent is recovered for reuse.

The gas-turbine combined-cycle power generation system is a power generation system that combines a gas turbine with a steam turbine. With a gas turbine operating at 1350°C, CO_2 emissions are reduced by approximately 20% compared to a pulverized coal-fired power generation system.

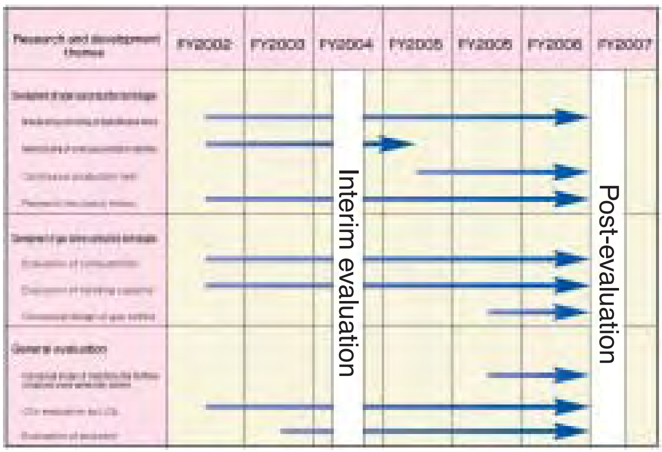
Coal is mixed with the solvent, and the mixture is pressurized and heated to dissolve the coal's organic portions into the solvent. Insoluble ash is treated by the settler with gravity. It is removed as residue coal. The solvent, containing the dissolved coal, is sent to the ion exchange vessels.

Conventional power generation system. Power is generated by combusting the residue coal.

6. Concept of Hyper-coal based power generation system



7. Research and development timetable



4D2. Low-rank Coal Upgrading Technology (UBC Process)

Research and development: Japan Coal Energy Center; Kobe Steel, Ltd.
Project type: Joint research of technologies applicable in coal-producing countries
Period: 2001-2004 (4 years)

Technology overview

1. Background and process overview

Brown and sub-bituminous coal, accounting for about 50% of coal reserves, are referred to as "low-rank coal." Applications are limited due to its low heating value and spontaneous combustibility. Unlike bituminous coal, however, much of the low-rank coal has low sulfur/ash content. Therefore, if it could be efficiently upgraded and converted into high-grade, high-heating coal, it would greatly contribute not only to a stable energy supply but also to environmental conservation. A low-rank coal upgrading technology (UBC process) has been developed to enable the effective use of such low-rank coal. This process, an adaptation of the slurry dewatering technique in the brown coal liquefaction process, consists of 3 stages: 1) slurry preparation/dewatering, 2) solid-liquid separation/solvent recovery, and 3) briquetting (Fig. 1).

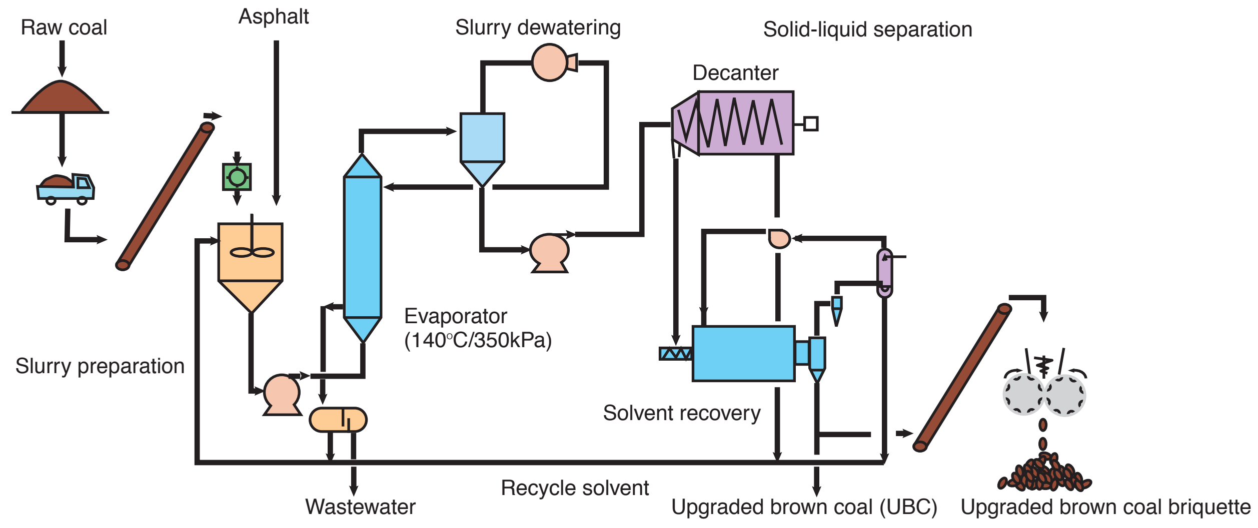


Fig. 1 UBC process for upgrading low-rank coal

During the slurry preparation/dewatering stage, after the pulverized high-moisture low-rank coal has been mixed with circulating oil (normally light petroleum oil), and then laced with heavy oil (such as asphalt), and heated in a shell and tube-type evaporator, moisture is recovered as water vapor. This water vapor is sent to the shell side of the evaporator, after being pressurized by a compressor, to use the waste-heat as a heating source, providing substantial energy savings during the dewatering stage. Low-rank coal also contains numerous pores and the moisture within them is removed in the course of evaporation. During that time, laced heavy oil is effectively adsorbed into the surface of the pores, thus preventing spontaneous combustion. Moreover, the water-repellant nature of heavy oil functions to prevent the re-adsorption of moisture and accumulation of the heat of wetting (Fig. 2).

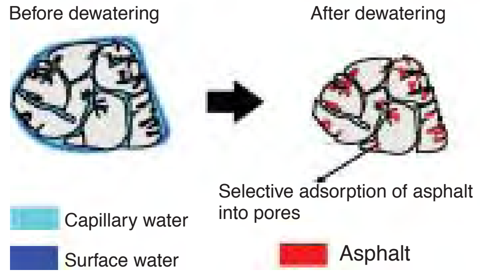


Fig. 2 Fundamentals of low-rank coal upgrading

At the stage of solid-liquid separation/solvent recovery, after most of the recycled solvent is recovered from the dewatered slurry by a decanter, the recycled solvent remaining in the pores of the upgraded coal is recovered by a tubular steam dryer.

Since the upgraded coal produced in the UBC process is still in a powder form, for transportation to non-local customers it is formed into briquettes. Using a double roll briquetter, the upgraded coal can easily be briquetted without the use of a binder. Photo 1 shows a picture of upgraded-coal briquettes.

2. Development target

1) Upgrading cost

Assuming that the FOB price of bituminous coal with a heating value of 6,500 kcal/kg is $20/ton, that of 4,500 kcal/kg sub-bituminous coal should be around $13/ton in calorific equivalents. When upgrading this coal to a calorific value of 6,500 kcal/kg, the treatment cost guideline should be set at $7/ton. However, taking into account the advantages of low-rank coal, such as its low ash content, the R&D team has set a development target to keep upgrading costs equal to or less than $10/ton.

2) Thermal efficiency in the upgrading process

The upgrading of low-rank coal needs to provide a higher thermal efficiency than that obtained from the direct firing of the same low-rank coal when considering the entire process involved, from UBC production to power generation. Thus, the minimum thermal efficiency target for the upgrading process has been set to 90%.

3. Development progress and results

The heating value of upgraded coal, though it varies depending upon the characteristics of the coal, has been improved to around 6,500kcal/kg, and its spontaneous combustion problem has also been successfully suppressed. It has also been confirmed that briquetted upgraded-coal is similar to normal bituminous coal when it comes to ease-of-handling and re-crushing.

Furthermore, upgraded coal, when combusted, quite easily burns itself out to leave almost no un-burned portion even under low-NOx combustion conditions, exhibiting excellent characteristics as a fuel.

Photo 1 Briquetted UBC

4. Future assignments and prospective commercialization

The Japan Coal Energy Center and the Research and Development Agency of the Ministry of Energy and Mineral Resources served as the driving force for building a 5 ton/day (on a raw coal basis) UBC process demonstration plant in Cirebon, Java Barat province, Indonesia. Operation of the demonstration plant was completed in 2005 (Photo 2).

In low-rank coal producing countries, including Indonesia, coal producers are highly interested in the UBC process and are hoping for early commercialization.

Photo 2 Low-rank coal upgrading demonstration plant

Reference

1) Toru Sugita et al., UBC (Upgraded Brown Coal) Process Development, Kobe Steel Engineering Reports, 53, 42, 2003.

5A1. Hydrogen Production by Reaction Integrated Novel Gasification Process (HyPr-RING)

Research and development: Japan Coal Energy Center; National Institute of Advanced Industrial Science and Technology; Ishikawajima-Harima Heavy Industries Co., Ltd.; Babcock Hitachi K.K.; Mitsubishi Materials Corporation; JGC Corporation

Project type: Subsidized by the Ministry of Economy, Trade and Industry

Period: 2000-2008 (9 years-planned)

Technology overview

1. Background

In addition to its position as the world's most abundant energy reserve, coal is used as an important primary energy source due to its economic advantages as well. Future consumption is expected to increase with economic growth as well as an increasing population.

Meanwhile, in response to global warming caused by CO_2, there is an earnest need to develop technology to use coal cleanly and more efficiently. In response, a process called HyPr-RING that enables the hydrogen necessary for future hydrogen-energy communities to be produced from coal is now under development for commercialization.

2. Theory of HyPr-RING process

HyPr-RING is a process in which a CO_2-sorbent, CaO, is directly added into a coal gasifier and the CO_2 generated by coal gasification is fixed as $CaCO_3$, together with the produced hydrogen. The reaction between CaO and H_2O produces the heat necessary for subsequent coal gasification in the gasifier. Within the gasifier, a series of reactions from equation (1) to equation (4) and the overall reaction of equation (5) take place.

$$CaO + H_2O \rightarrow Ca(OH)_2\,; \quad \Delta H^{o}_{298} = -109\,kJ/mol \quad (1)$$

$$C + H_2O \rightarrow CO + H_2\,; \quad \Delta H^{o}_{298} = 132\,kJ/mol \quad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2\,; \quad \Delta H^{o}_{298} = -41.5\,kJ/mol \quad (3)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O\,; \quad \Delta H^{o}_{298} = -69\,kJ/mol \quad (4)$$

$$C + 2H_2O + CaO \rightarrow CaCO_3 + 2H_2\,; \quad \Delta H^{o}_{298} = -88\,kJ/mol \quad (5)$$

This overall reaction is an exothermic reaction with C, H_2O, and CaO as initial reactants. This means that, in theory, there is no need for external heat. It was also discovered that CO_2 fixation enhances reactions (2) and (3) for H_2 generation. Figure 1 shows the process concept of HyPr-RING. $CaCO_3$ is regenerated by calcination into CaO for its recycle as a sorbent. Most of the heat energy required for calcination is carried as the chemical energy of CaO and made available for coal gasification to produce H_2 in the gasifier.

How is this different from conventional gasification?

Conventional gasification secures the heat necessary for gasification through a partial combustion of coal, with a reaction taking place in the gasifier expressed by the following equation:

$$C + 0.5O_2 + 0.5H_2O \rightarrow 0.5CO_2 + 0.5CO + 0.5H_2 \quad (6)$$

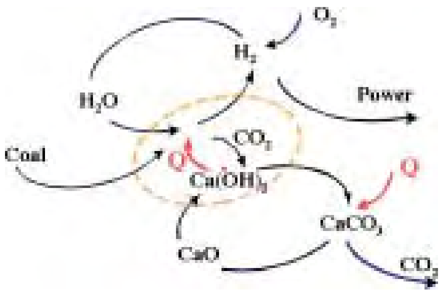


Fig. 1 Concept of HyPr-RING process

Gasification gas must be sent through a low-temperature shifter and then exposed to a low-temperature absorbent such as amine for CO_2 separation. At that time, the amount of CO_2 gas separated is one mole per mole of hydrogen.

On the other hand, the HyPr-RING process uses dry CaO to absorb CO_2 in the furnace (650°C, 30 atm). In this case, heat is released during CO_2 absorption to maintain a high temperature in the gasifier.

Here, post-CO_2 absorption $CaCO_3$ is returned to CaO by calcination (reproduction) and, at that time, 50-80% of the thermal energy required is converted into CaO for reuse in the gasifier (Fig. 2).

As seen from equation (5), 2-mole hydrogen production from one mole of carbon is another important feature.

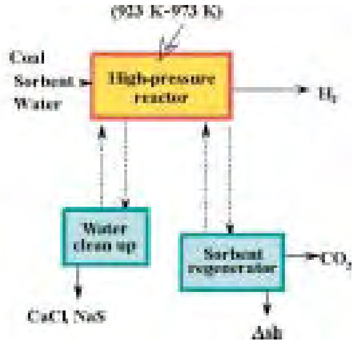


Fig. 2 Hydrogen production using HyPr-RING process

Table 1 CO_2 separation energy and temperature level

	HyPr-RING (CaO absorption process)	Partial combustion (Monoethanolamine absorption process)
Heating value of carbon (C→CO_2)	393 kJ/mol	393 kJ/mol
CO_2 absorption energy	178 kJ/mol	84.5 kJ/mol
CO_2/H_2 generation ratio	0.5 mol/mol	1 mol/mol
CO_2 separation energy per mole of H_2 generated	89 kJ/mol	84.5 kJ/mol
Temperature level	973-1073 K	about 323 K

3. Characteristics of HyPr-RING process

Cold gas efficiency

The HyPr-RING process gasifies the easy-to-gasify portion of coal under low-temperature (600-700°C) conditions into hydrogen and uses the remaining difficult-to-react char as fuel for $CaCO_3$ calcination.

Figure 3 shows an example of a HyPr-RING process configuration with a fluidized-bed gasifier and an internal combustion-type calcining furnace. For product gas composition of 95% H_2 and 5% CH_4, the cold gas efficiency proved to be about 0.76.

CaO absorbent

At the gasifier inlet, where the temperature is low, CaO first reacts with H_2O to produce $Ca(OH)_2$, providing heat-to-coal pyrolysis. Then, at a high-CO_2 partial pressure region, $Ca(OH)_2$ absorbs CO_2 to produce $CaCO_3$, and releases heat. This heat is used for the gasification of char. To prevent CaO from becoming less active due to high-temperature sintering, a method of absorbing CO_2 in the furnace, by way of $Ca(OH)_2$, is employed. Gasification at a temperature as low as possible is also employed to prevent the eutectic melting of calcium minerals. In such cases, unreacted product carbon can be used as a heat source for CaO reproduction.

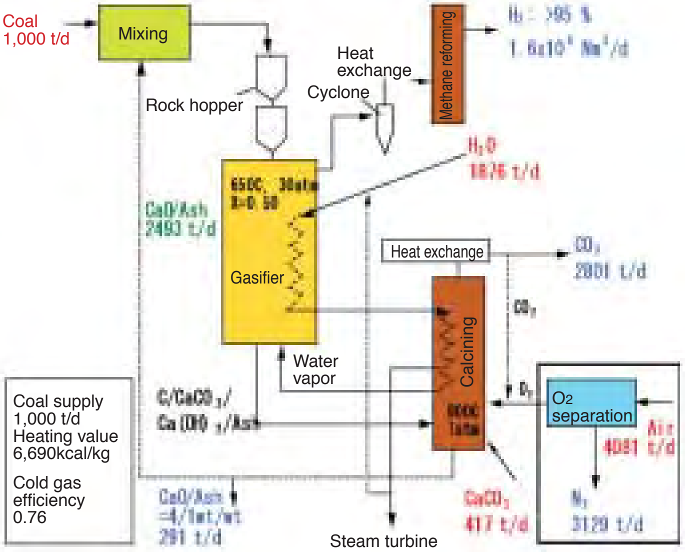


Fig. 3 Analysis of HyPr-RING process

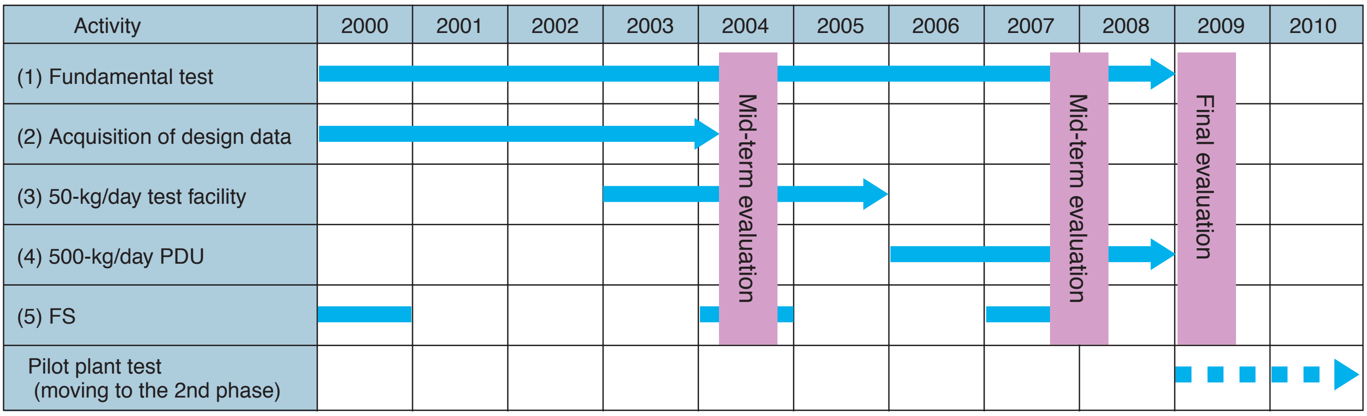
4. Project overview

Under this project, which commenced in 2000, process configuration identification and FS through testing with batch/semi-continuous equipment were paralleled with a variety of factor tests required. In and after FY2003, it is expected that 50-kg/day (coal base) continuous test equipment will be fabricated for continuous testing and then, based on the results, running tests and a FS of a 5 ton/day-scale pilot plant are to be carried out in and after 2006 to establish a commercialization process. Table 2 shows development targets of the project and Table 3 shows, the project timetable.

Table 2 Targets

Item	Target
1. Gasification efficiency 2. Product gas purity 3. CO_2 recovery	1. Cold gas efficiency: 75% or greater 2. Sulfur content of product gas: 1ppm or less 3. High-purity CO_2 recovery rate: 40% or greater of inputed coal carbon to be recovered (per-unit of energy CO_2 exhaust to be less than that from natural gas)

Table 3 Development timetable



Activity	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
(1) Fundamental test	▬	▬	▬	▬	Mid-term evaluation	▬	▬	▬ Mid-term evaluation	▬ →	Final evaluation	
(2) Acquisition of design data	▬	▬	▬	▬ →							
(3) 50-kg/day test facility				▬	▬ →						
(4) 500-kg/day PDU							▬	▬	▬ →		
(5) FS	▬				▬			▬			
Pilot plant test (moving to the 2nd phase)										■ ■ ■	■ ■ ▶

References

1) Shiying Lin, Yoshizo Suzuki & Hiroyuki Hatano, Patent No. 29791-49, 1999.
2) Energy Technology and the Environment, Editors: A. Bisio and S. Boots, John Wiley & Sons, New York, 1995.

5A2. CO_2 Recovery and Sequestration Technology

Technology overview

1. CO_2 recovery technology

(1) CO_2 recovery technology (for natural gas, syngas, and flue gas)

CO_2 separation/recovery is widely prevalent in the natural gas and syngas fields and has been carried out for decades. The CO_2 in natural gas is not only useless because it decreases the caloric value of natural gas, but also because it creates problems at LNG/ethane recovery plants by solidifying into dry ice. CO_2 is hence removed to prevent such problems.

In a plant where natural gas or naphtha is reformed to manufacture H_2, CO_2 is separated after being converted from the CO produced with hydrogen as syngas. In an ammonia/urea plant, CO_2 is separated from the gas mixture of H_2, N_2, and CO_2 to produce urea, using H_2/N_2-derived synthetic ammonia and separated CO_2.

Previously, however, CO_2 separation/recovery from flue gas was not in such large demand, finding limited applications only in food processing and dry ice. When CO_2 is separated from natural gas or syngas, the separation is relatively easy because of the high pressure of the gas. To the contrary, CO_2 separation/recovery from flue gas is difficult in many technological respects due to the very low pressure of flue gas as well as the presence of oxygen, SOx, NOx, and soot and dust in the flue gas.

(2) Necessity to recover CO_2 from fixed sources

Most fossil fuels (oil, natural gas, and coal) in the world are used as fuel for boilers, gas turbines, and internal combustion engines, releasing CO_2 into the atmosphere as exhaust gas. As a result, it is alleged that the atmospheric concentration of CO_2 has increased, resulting in global warming, which can only be prevented through the mitigation of CO_2 emissions. There are, however, many difficulties in recovering and sequestering CO_2 from movable bodies such as automobiles and vessels, naturally rendering it easier to recover CO_2 from stationary sources, like boilers, gas turbines, etc.

(3) Characteristics and superiority of technology to recover CO_2 from exhaust gas

The Kansai Electric Power Co., Inc. and Mitsubishi Heavy Industries, Ltd. began a joint R&D program in 1990 to recover CO_2 from the exhaust gas of power plants and other facilities as a global-warming countermeasure. First, they assessed the conventional "monoethanolamine" (MEA) liquid absorbent-based technology considered at that time a CO_2 recovery process that could save the largest amount of energy. It is a process developed by the former Dow Chemical Co. and later assigned to Fluor Daniel, Inc. This MEA-based technology was found disadvantageous for use in large plants as a measure against global warming because of such problems as the large amount of energy required for CO_2 recovery and the great loss in the liquid absorbent due to its rapid degradation. Kansai Electric Power and Mitsubishi Heavy Industries started with basic research to explore a new liquid absorbent, resulting in the successful development of a novel energy-saving liquid absorbent less prone to degradation. It has already been put into practical use for the manufacture of urea in Malaysia.

2. CO_2 sequestration technology

Geological sequestration and ocean sequestration are being widely studied and a commercial project of the former has already begun. Geological CO_2 sequestration is being carried out, using the Enhanced Oil Recovery (EOR) method or the coal seam sequestration-accompanied Coal Bed Methane Recovery method. Aquifer sequestration and sequestration into closed oil/gas fields are options as well, if the only objective is CO_2 sequestration. Figure 1 shows a conceptual view of CO_2 recovery-EOR combination.

CO_2-EOR commercialization started in the 1970's mainly in the United States, enhancing oil production by approximately 200,000 barrels/day. Outside the United States, Canada, Turkey, and Hungary also utilize the CO_2 recovery-EOR combination.

Underground aquifers are widely distributed on the earth wherever sedimentary layers are located. Even in Japan, where aquifers are scarce and small in structure because of Japan's volcanic and earthquake history, surveys are underway for possible CO_2 sequestration sites. If a geological underground layer has cavities, CO_2 can be sequestered in these cavities, which indigenously contain water (mainly salt water), by pumping in CO_2, thereby displacing the water. This is already underway in Norway. For Japan, Norway-like CO_2 sequestration into aquifers distributed over continental shelves are considered the most realistic.

Other than into aquifers, CO_2 can also be sequestered into closed oil/gas fields where production has already been terminated. Closed oil/gas fields once were active oil/gas fields because their geological structures did not permit oil/gas leaks. Therefore, such closed oil/gas fields are considered secure CO_2 sequestration sites.

Photo 1 Conceptual view:
CO_2 recovery from power plant flue gas for EOR

Reference

Masaki Iijima et al., "CO_2 Recovery/Effective Utilization/Fixation and Commercialization," MHI Technical Journal, 39 (5), 286, 2002.

5A3. CO_2 Conversion Technology

Technology overview

1. Urea production

At present, urea is produced from ammonia and carbon dioxide, which is generated from inexpensive natural gas (off-gas) during the manufacture of ammonia. When urea is synthesized with natural gas as a raw material, however, the available CO_2 may be insufficient in view of the balance between ammonia and off-gas CO_2. In such cases, CO_2 is recovered from the exhaust gas of the steam reformer, which produces hydrogen and CO from natural gas, to supply it for urea synthesis to adjust the ammonia-CO_2 balance, thereby enabling urea to be produced in large quantities. A plant Mitsubishi Heavy Industries, Ltd. delivered to Malaysia PETRONAS Fertilizer Sdn. Bhd. (Photo 1) matches this purpose.

Photo 1 Urea plant

2. Methanol production

Methanol is now also manufactured mainly with natural gas as the feedstock. If H2 and CO are synthesized by steam-reforming the natural gas, then the H_2:CO ratio is 3:1. On the other hand, for methanol synthesis, the best H_2:CO ratio is 2:1, and the output of methanol can be maximized through the recovery of CO_2 from steam reformer flue gas, allowing the addition of a meaningful amount of CO_2 into the process. At present, active planning for CO_2 addition is underway to improve the production capacity of Saudi Arabian methanol plants.

Figure 1 shows a system where, in the process to produce methanol with natural gas as the feedstock, CO_2 is recovered from steam reformer flue gas to optimize the H_2:CO ratio for methanol synthesis, thereby enhancing methanol production.

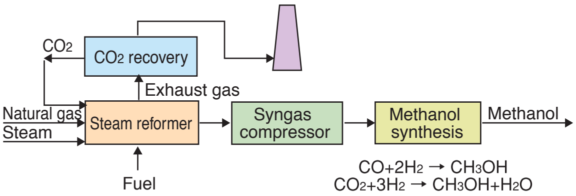


Fig. 1 CO_2 recovery from flue gas for enhanced methanol production

3. DME (dimethyl ether) production

DME is currently synthesized from methanol. The process is similar to that used for the above-mentioned methanol production.

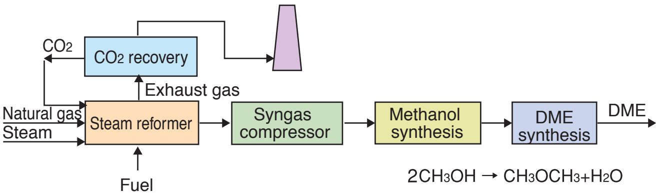


Fig. 2 CO_2 recovery from flue gas-integrated DME production system

4. GTL production

GTL, or Gas-to-Liquid, generally refers to a process to synthesize kerosene and light oil by the Fischer-Tropsch Process (FT Process). For this GTL synthesis, as in the case of methanol, it is necessary to adjust the H_2:CO ratio to 2:1 and recover the same volume of CO_2 from the steam reformer flue gas for use in the process, also as in methanol production, to enable the H_2:CO ratio to be adjusted.

The system recovers and recycles CO_2, which does not contribute to the reaction from the FT synthesis process, to the stage prior to steam reforming.

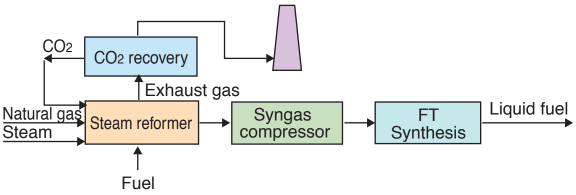


Fig. 3 CO_2 recovery from flue gas-integrated liquid fuel production system

Reference

Masaki Iijima et al., "CO_2 Recovery/Effective Utilization/Fixation and Commercialization," MHI Technical Journal, 39 (5), 286, 2002.

5A4. Oxy-fuel Combustion (Oxygen-firing of Conventional PCF System)

Research and development: Japan Coal Energy Center; J-POWER; Ishikawajima-Harima Heavy Industries, Co., Ltd.; Taiyo Nippon Sanso Corporation (Nippon Sanso Corp.); and Institute of Research and Innovation
Project type: Coal Production and Utilization Technology Promotion Grant
Period: 1992-2000 (8 years), 2004-2005 (2 years)

Technology overview

1. Background and the oxy-fuel combustion system

The Kyoto Protocol entered into force in February 2005, and now many countries are working actively toward the second commitment period starting in 2013. From a global viewpoint, however, thermal power plants are releasing CO_2 in large quantities, which indicates the necessity for a power generation system with CO_2 recovery and storage capabilities. Among all the fossil fuels used at thermal power plants, coal produces the greatest amount of CO_2 per calorific unit value.

In the process of recovering CO_2 through oxy-fuel combustion as shown in Figure 1, O_2 is separated from combustion air and used for burning coal. In this process, it is theoretically possible to improve the CO_2 concentration in the emissions to 90% or more, and to easily recover CO_2.(1) When this technology is applied to power plants for the purpose of controlling the flame temperature, flue gas (mostly CO_2) is recirculated and mixed with O_2. With this technology, it has been confirmed that the process characteristics help reduce NOx emissions. Expectations for this system are high because it represents a direct CO_2 recovery method that is better than other CO_2 recovery systems in terms of economical efficiency and technological feasibility.

In the future, it will be increasingly necessary to establish a coal-fired power plant with CCS (Carbon Dioxide Capture and Storage). In this respect, it will be important to integrate the power generating unit and the CO_2 recovery and storage capabilities.

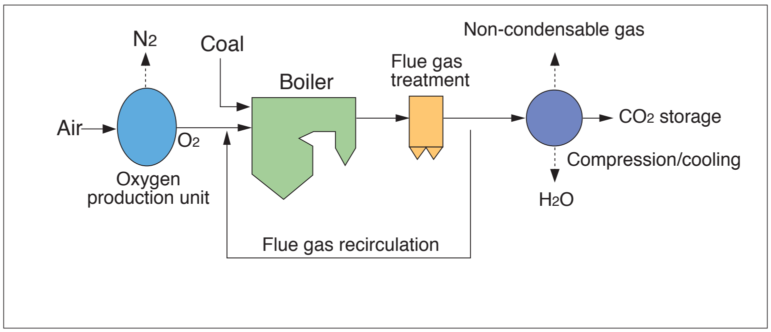


Fig. 1 Concept of oxy-fuel combustion with CCS

2. Development results

An application study on an existing 1000MWe coal-fired power plant was carried out to examine the system structure and the boiler furnace, as well as the operating and economic efficiency.

Table 1 and Figure 2 show the specifications of the existing 1,000 MWe power plant when the oxy-fuel combustion system was introduced. In applying oxy-fuel combustion, motive power is necessary for oxygen production and CO_2 recovery. The station service power occupies up to 30% of the total electricity generated, and the net efficiency is 30%. The amount of CO_2 recovered is about 800 t/hr (or about 5 million tons per year.)

According to our calculation, the cost for CO_2 separation and recovery is approximately 3,000 yen per ton-CO_2. In this process, the initial cost and the operational and maintenance costs for oxygen production account for more than half of the total cost, and thus it is hoped that innovative oxygen production technology will be developed.

Table 1 Specifications of a plant with oxy-fuel combustion system

Specifications	Unit	Air combustion	Oxy-fuel combustion
Rated output	MWe	1050	1050
Net efficiency	%	40	30
Station service power	%	5	30
Availability	%	80	80
Coal consumption (Australian coal)	t/h	330	330
Oxygen supply	km^3N/h	480 (in Air)	430
CO_2 recovery rate	%	–	95
CO_2 recovery	t/hr	–	802

3. Demonstration project in Australia

On the basis of the study results described above, demonstrative studies are now underway for applying oxy-fuel combustion to an existing plant.(4) These studies include an Australia-Japan joint project in which an oxy-fuel combustion demonstration plant will be completed by the end of 2008. This project aims to recover and store CO_2 from an existing power plant. The outline of the project is as follows:

The project is being implemented at a power generation plant in the Callide-A power plant's No. 4 unit owned by CS Energy on the east coast of Australia. This unit was selected because it has adequate capacity as a demonstration plant. Additionally, it is currently out of service and thus is available for modifications.

The storage site is planned to be located in a depleted gas field, about 250 km to the west of the power plant. This site was chosen because it is not far away from the power plant, the estimated CO_2 storage capacity is sufficient, and the reservoir characteristics such as permeability and porosity are adequate.

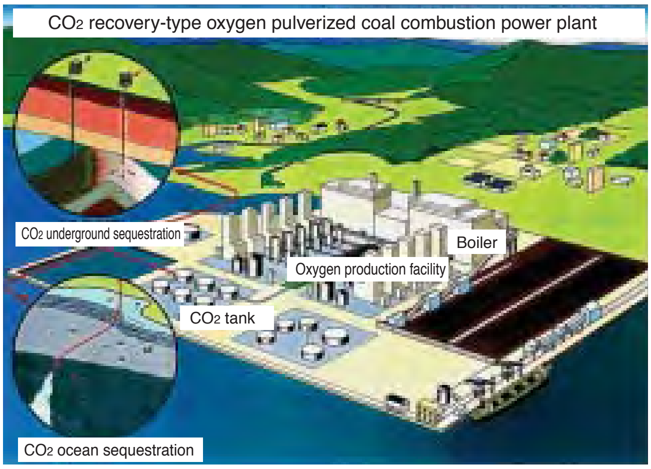
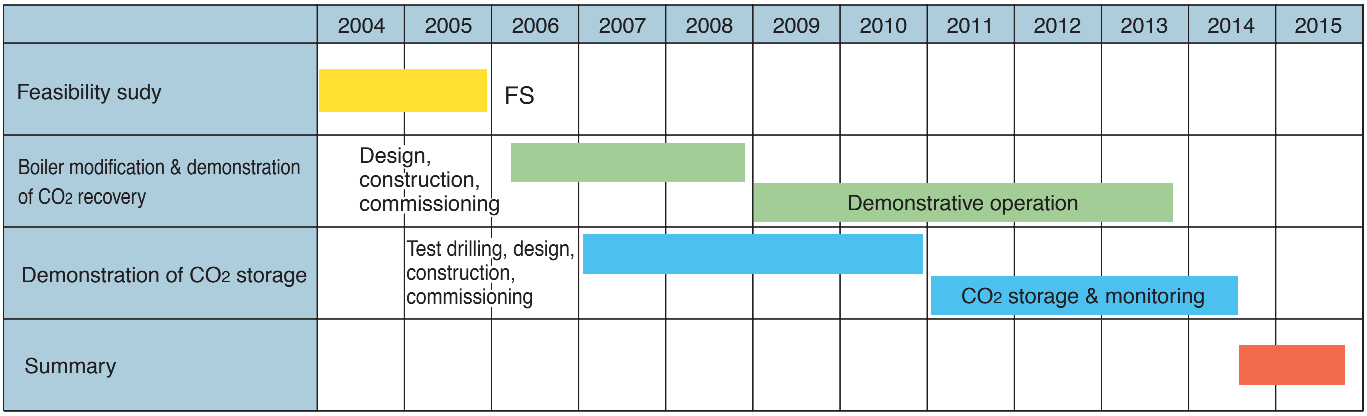


Fig. 2 Image of CO_2 recovery-type power plant applying oxygen combust

The entire project schedule is shown in Table 2. For this demonstration project, Australia and Japan jointly conducted a feasibility study from FY2004 to FY2005. Based on its results, detailed studies began in 2006, aiming at completing the plant by the end of 2008. Demonstrative operation of the oxy-fuel combustion system will be carried out for five years after completion. Storage of captured CO_2 will start in FY2011, and thus demonstration and monitoring of CO_2 storage will be carried out for three years.

Table 4 Project schedule



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Feasibility sudy	🟨	🟨	FS									
Boiler modification & demonstration of CO_2 recovery	Design, construction, commissioning		🟩	🟩	🟩	🟩 Demonstrative operation	🟩	🟩	🟩	🟩		
Demonstration of CO_2 storage		Test drilling, design, construction, commissioning		🟦	🟦	🟦	🟦	🟦 CO_2 storage & monitoring	🟦	🟦	🟦	
Summary											🟥	🟥

4. Issues and feasibility of practical application

As described above, the demonstration of a power plant using oxy-fuel combustion is now about to start. Hopefully by the year 2010, it will be demonstrated that the system is reliable and economically efficient for CO_2 recovery. It is necessary first and foremost to ensure the steady implementation of the Australia-Japan demonstration project, so that it will be the first step toward commercialization. The following topics will be the subjects of the demonstration and further studies:

(1) Stability and safety in the operation of a power plant using oxy-fuel combustion

(2) Stable operation of a CO_2 recovery system

(3) Efforts for reducing costs and enhancing efficiency

(4) Total system optimization for power generation and CO_2 recovery/transportation/storage

References

1) K. Kimura et al., JSME-ASME Int. Conf. On Power Eng.-93, Tokyo, Sept. 1993.
2) NEDO, "Report on the Clean Coal Technology Promotion Project 2004: Study on the Application of Oxygen Combustion Technology to an Existent Pulverized Coal-Fired Power Plant".
3) NEDO, "Report on the Clean Coal Technology Promotion Project 2005: Study on the Application of Oxygen Combustion Technology to an Existent Pulverized Coal-Fired Power Plant".
4) C. Spero, Proc. Clean Coal Day in Japan 2004, Advanced Clean Coal Tech. Int. Symp. Tokyo, Sept. 2004.

5B1. SOx Reduction Technology

Technology overview

1. Background

Sulfur oxides (SOx, mainly SO_2) are regulated by a "K-value" control, which uses exhaust heights and regional coefficients to limit SOx emissions. "Total amount control" is a term used in Japan to define the total emissions from the whole of a region. To comply with these regulations, flue gas desulfurizers were commercialized in 1973. Efforts to improve their performance and lower costs have been ongoing. At present, most pulverized coal-fired thermal power plants are equipped with wet limestone and gypsum-based desulfurization systems. Furthermore, a wet desulfurization process requiring no wastewater treatment is now under development.

2. Technology

(1) Wet limestone-gypsum process

Research and development: Mitsubishi Heavy Industries, Ltd.; Babcock Hitachi K.K.; Ishikawajima-Harima Heavy Industries Co., Ltd.; Chiyoda Corporation; Kawasaki Heavy Industries, Ltd.; others

Overview

There are two limestone-gypsum processes; a soot-separation process, in which a dust (cooling) tower is installed upstream for dust collection and HCl/HF removal and cooling, and a soot-mixed process without such a dust (cooling) tower. The soot-separation process is used when high-purity gypsum containing no soot or dust is desired. At present, however, more and more systems employing the soot-mixed process, which is less expensive to install, are being installed since high-performance dust collection devices, such as an advanced low-temperature electrostatic precipitator, which lowers soot/dust concentrations, have been developed.

In the absorption tower, on the other hand, a water-mixed limestone slurry is reacted with SO_2 within the exhaust gas for the recovery of sulfur contents as gypsum ($CaSO_4$-$2H_2O$).

The overall reaction is as follows:

$CaCO_3+SO_2+0.5H_2O \rightarrow CaSO_3\text{-}0.5H_2O+CO_2$

$CaSO_3\text{-}0.5H_2O+0.5O_2+1.5H_2O \rightarrow CaSO_4\text{-}2H_2O$

There are two types of absorption towers, as shown in Figure 1: a $CaSO_3$-$0.5H_2O$ separate tower oxidation system and a comprehensive single tower oxidation system. At present, single tower oxidation systems are less expensive to install and operate and their use is increasing annually. There are several methods to have recycled absorption liquid come into contact with SO_2 in the absorption tower section; the "spray method," which sprays the absorption liquid, the "grid method," which spreads absorption liquid on the surface of a grid-like pad, the "jet-bubbling method," which blows exhaust gas into the absorption liquid, and the "water-column method," in which absorption liquid flows in the absorption tower.

For developing countries, a simple desulfurizer installable in the flue gas duct or at the lower part of a smoke stack has also been commercialized.

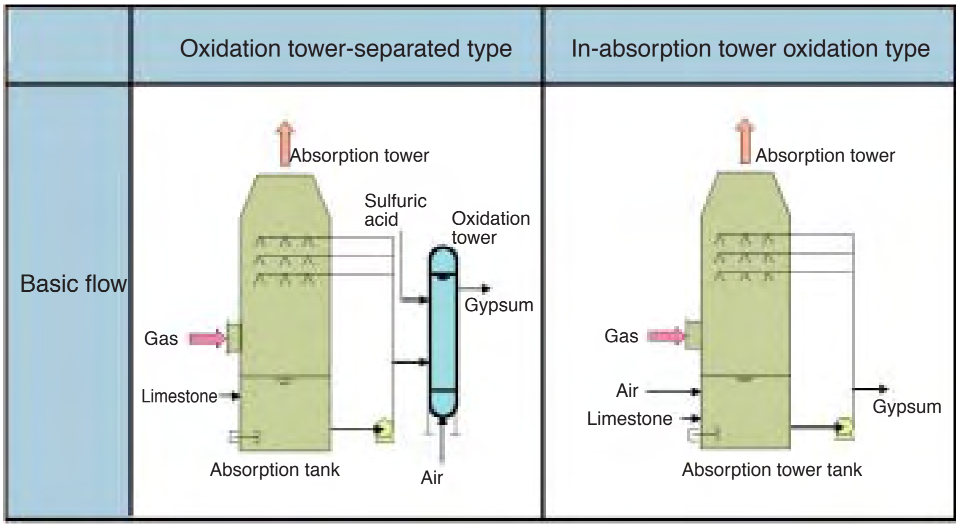


Fig. 1 Limestone-gypsum process-based desulfurizers

(2) Coal ash-based dry desulfurization process

Research and development: Hokkaido Electric Power Co., Inc.; Hitachi, Ltd.; Babcock Hitachi K.K.
Project type: Subsidized development of oil-alternative energy-related technology for commercialization
Development period: 1986-1989

Overview

The coal ash-based dry desulfurization process was one of the technologies developed to make effective use of coal ash. This is a process to produce a new absorbent from limestone, calcium hydroxide ($Ca(OH)_2$) and spent absorbent. By using the newly produced absorbent, SOx is removed from the flue gas. Figure 2 shows an outline of this process, which also includes a stage to manufacture the absorption agent. The desulfurization reaction allows $Ca(OH)_2$ to remove SO_2. Temperatures are maintained between 100-200°C, where an SOx removal efficiency of 90% or greater can be attained. The process can also remove dust and NOx, with a NOx removal efficiency of approximately 20% and a dust collection efficiency of 96% or more. By 2003, the technology had been installed at Hokkaido Electric Power's Tomatoh-Atsuma Thermal power plant No. 1 unit (350MW), where the equipment is being used to treat one-half of the flue gas.

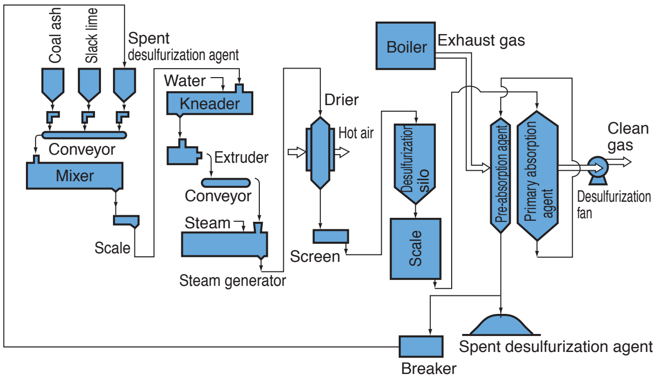


Fig. 2 Coal ash-based dry desulfurization process

(3) Spray dryer process

Research and development: The Electric Power Development Company; Mitsubishi Heavy Industries, Ltd.; Hokkaido Electric Power Co., Inc.
Project type: Voluntary under the Green Aid Plan

Overview

The spray dryer process is a so-called "semi-dry process," where water is added to burned lime (CaO) to make a slack lime ($Ca(OH)_2$) slurry, which is sprayed into a spray dryer, causing the SO_2 in the flue gas to react with $Ca(OH)_2$, and to be removed. Within the dryer, the desulfurization reaction and limestone drying take place simultaneously, giving a particle mixture of gypsum ($CaSO_4$-H_2O) and calcium sulfite ($CaSO_3$-$0.5H_2O$). These particles are recovered at a down-stream precipitator. Since this process is not adequate for good-quality gypsum and, moreover, ash remains in the mix, desulfurized particles are disposed of as waste. J-POWER, as part of the "Green Aid Plan," installed a spray dryer desulfurizer with an exhaust gas treatment capacity of $300Km^3N/h$ (one-half of total exhaust) at the Huangdao power plant No. 4 unit (210MW) in Qingdao, China. It is currently in operation and attained a 70% desulfurization rate in verification tests (Oct. 1994 through Oct. 1997).

(4) Furnace desulfurization process

Research and development: Hokkaido Electric Power Co., Inc.; Kyushu Electric Power Co., Inc.; J-POWER; Chugoku Electric Power Co., Inc.; Mitsubishi Heavy Industries, Ltd.; Ishikawajima-Harima Heavy Industries Co., Ltd.; Kawasaki Heavy Industries, Ltd.
Project type: Voluntary

Overview

The furnace desulfurization process is used for fluidized-bed boilers. Limestone to be used for desulfurization is mixed and combusted with the coal, causing the following reaction to remove SO_2 at a furnace temperature of 760-860°C:

$CaCO_3 \rightarrow CaO+CO_2$ $CaO+SO_2 \rightarrow CaSO_3$

At present, this process is employed at J-POWER's Takehara thermal power plant No. 2 unit normal-pressure fluidized-bed boilers as well as the pressurized fluidized-bed boilers of Hokkaido Electric Power's Tomatoh-Atsuma thermal power plant, Kyushu Electric Power's New Kanda thermal power plant, and Chugoku Electric Power's Osaki thermal power plant. In pressurized fluidized-bed boilers, limestone does not breakdown into CaO due to the high partial pressure of CO_2, but SO_2 is removed in accordance with the following reaction:

$CaCO_3+SO_2 \rightarrow CaSO_3+CO_2$

References

1) "Introductory Course: Environmental Preservation Technology/Equipment for Thermal Power Plants IV Desulfurization Equipment," Thermal/Electronic Power Generation Vol. 41 No. 7, 911, 1990.
2) Kudo et al., "Coal Ash-Based Dry Desulfurizer Development," Thermal/Electronic Power Generation, Vol. 41, No. 7, 911, 1990.
3) "Coal Ash-Based Dry Flue Gas Desulfurizer" pamphlet, Hokkaido Electric Power.
4) General View of Thermal Power Generation, Institute of Electric Engineers, 2002.

5B2. NOx Reduction Technology

Technology overview

1. Background

Nitrogen oxide emissions are regulated, with acceptable concentration levels set according to the type of fuel and the size of the boiler. However, with the recent stiffening of regulations, some regions are subject to a "total amount control," which provides for a region-wide overall emissions level as is the case with sulfur oxide emissions. To comply with these regulations, flue gas denitration equipment was commercialized in 1977, and ongoing efforts have been made to improve the durability of DeNOx catalysts as well as to reduce costs. The Selective Catalytic Reduction (SCR) process is used to decompose nitrogen oxides, mainly through the use of ammonia.

2. Technology

(1) Selective catalytic reduction process

Research and development: Mitsubishi Heavy Industries, Ltd.; Ishikawajima-Harima Heavy Industries Co., Ltd.; Babcock Hitachi K.K.

Overview

In this process, ammonia (NH_3) is blown into exhaust gas, allowing the ammonia (NH_3) to selectively react with nitrogen oxides NOx (NO, NO_2), and decompose them into water (H_2O) and Nitrogen (N_2). In the DeNOx reactor, since soot and dust are present in the exhaust gas, a grid- or plate-like catalyst is mainly used, as shown in Figure 1. The catalysts, as shown in Photo 1 and Photo 2, are installed in the reactor to react with the NH_3 blown into the catalyst layer from its inlet, allowing NOx (NO, NO_2) to breakdown into water vapor (H_2O) and nitrogen (N_2). The catalyst is mainly composed of TiO_2, to which vanadium (V), tungsten (W), and the like are added as active ingredients.

$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$

The temperature at which the catalyst attains optimal performance is 350°C. At a temperature lower than this, SO_3 in the exhaust gas reacts with NH_3, producing ammonium hydrogen sulfate (NH_4HSO_4) that covers the surface of the catalyst, thereby reducing the ability to remove NOx. At a temperature higher than 350°C, the NH_4HSO_4 decomposes, improving the removal of NOx regardless of the SO_3 concentration. At a temperature above 400°C, NH_3 is oxidized and its volume decreases, thereby reducing its ability to remove NOx. The process is also designed to limit NH_3 leaks from the reactor to 5ppm or less. If a significant quantity should leak, it will react with the SO_3 in the exhaust gas, producing NH_4HSO_4, which clogs the piping when separated out by an air pre-heater.

The NOx removal efficiency is around 80-90% for pulverized coal-fired thermal power plants. On the other hand, measures to equally disperse and mix the NH_3 with the exhaust gas as well as to create greater uniformity of the exhaust gas flows to cope with growing boiler sizes have been developed. These include placing a current plate, called a "guide vane" at the gas inlet, or dividing the gas inlet into grids, each to be equipped with an NH_3 injection nozzle.

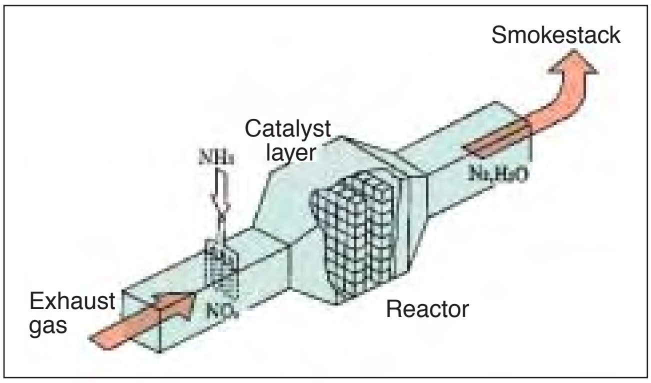


Fig. 1 Selective contact reduction method denitration process

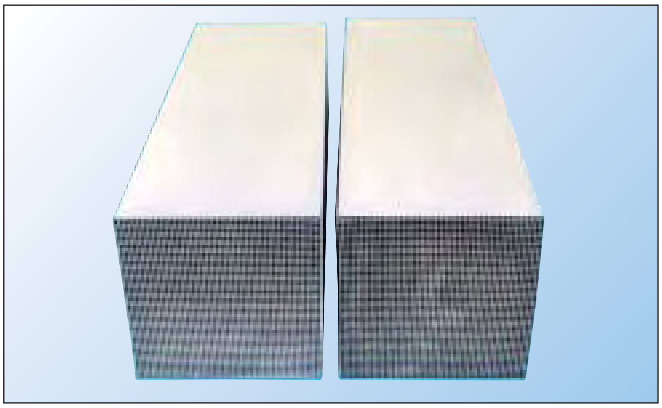


Photo 1 Grid-like catalyst

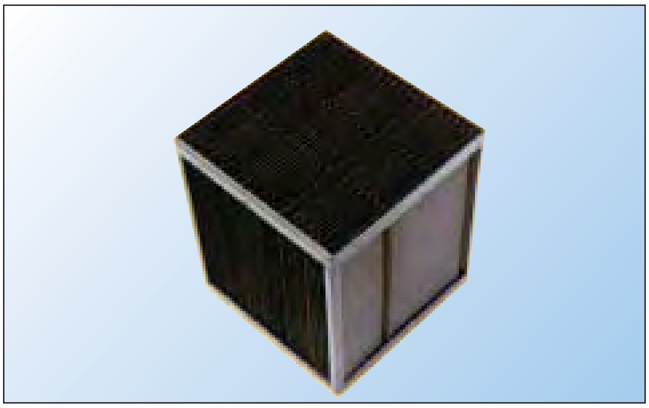


Photo 2 Plate-like catalyst

(2) Selective non-catalytic reduction (SNCR) process

Research and development: Chubu Electric Power Co., Inc.; Mitsubishi Heavy Industries, Ltd.
Project type: Voluntary

Overview

SNCR is a process to, as shown in Figure 2, blow NH_3 into the boiler section where the exhaust gas temperature is 850-950°C and to breakdown NOx into N_2 and H_2O without the use of a catalyst. Despite the advantages of not requiring a catalyst and its lower installation costs, the NOx removal efficiency is as low as 40% at an NH_3/NOx molar ratio of 1.5. Because of this, it is used in regions or equipment where there is no need for a high NOx removal efficiency. More NH_3 is also leaked than with the selective contact reduction method, requiring measures to cope with NH_4HSO_4 precipitation in the event of high SO_3 concentrations in the exhaust gas.

This technology is mainly used at small commercial boilers and refuse incinerators. With respect to thermal power plant applications, this technology has only been installed at Chubu Electric Power's Chita thermal power plant No. 2 unit (375kw), in 1977.

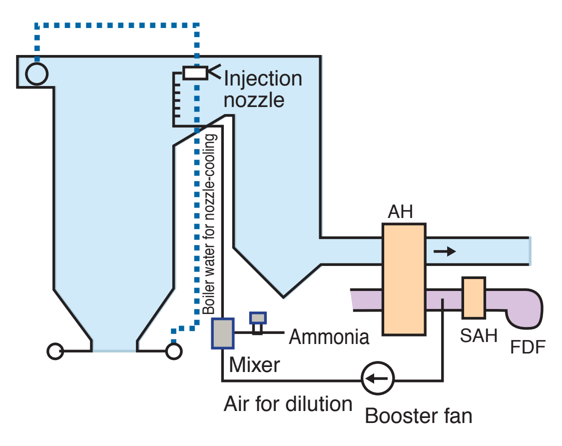


Fig. 2 Selective non-catalytic denitration NOx removal process

(3) Radical injection method

Research and development: Japan Coal Energy Center
Project type: Subsidized coal production/utilization technology promotion
Development period: 1999-2002

Overview

In the radical injection method, as shown in Figure 3, argon plasma is injected into NH_3, generating NH_2 plasma and other plasmas, which are then blown into the boiler to decompose NOx into N_2 and H_2O. The target for this technology is to attain an NOx concentration of 10ppm or less.

At present, basic research is underway at the Japan Coal Energy Center, with commercialization expected around 2010.

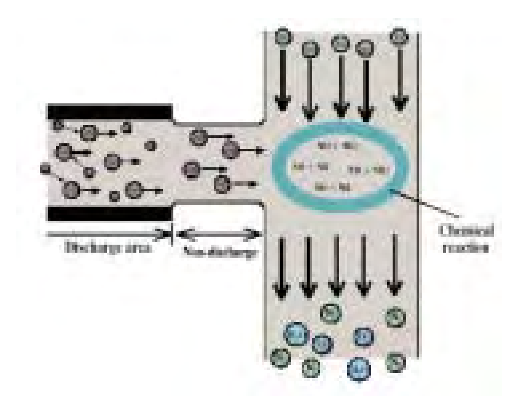


Fig. 3 Overview of radical injection method

References

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2) Tadamasa Sengoku et al., "Selective Non-Catalytic Denitration Method for Boilers," Thermal/Nuclear Power Generation, Vol. 29, No. 5, 1978.
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5B3. Simultaneous De-SOx and De-NOx Technology

Technology overview

1. Background

The technology behind the wet desulfurization process has also matured but requires a significant amount of service water as well as advanced wastewater treatment measures. Meanwhile, an already commercialized ammonia-based selective catalytic reduction (SCR) process requires not only long-term control of expensive DeNOx catalysts but also measures to prevent ammonia leaks. Development efforts are, therefore, underway for a dry combined desulfurization DeNOx method to remove NOx and SOx simultaneously without requiring any service water, wastewater treatment, or a DeNOx catalyst.

2. Technology

(1) Active carbon adsorption method

Research and development: J-POWER; Sumitomo Heavy Industries, Ltd.; Mitsui Mining Co., Ltd.
Project type: Voluntary support project for coal utilization promotion

Overview

The active carbon adsorption method causes a reaction between SO_2 in exhaust gas and injected NH_3 on active carbon at 120-150°C, thereby converting SO_2 into ammonium hydrogen sulfate (NH_4HSO_4) and ammonium sulfate ($(NH_4)_2SO_4$) for adsorption/removal while decomposing NOx into nitrogen and water as does the SCR process. Figure 1 shows the process. The moving-bed adsorption tower (desulfurization tower) removes SO_2 in the first-stage and, in the second stage (denitration tower), NOx is decomposed. This method first removes SOx and then NOx since, as shown in the figure, the presence of high-concentration SO_2 tends to decrease the effectiveness of NOx removal.

Active carbon that has absorbed NH_4HSO_4 is heated to 350°C or higher in the desorption tower to desorb NH_4HSO_4 after decomposing it into NH_3 and SO_2, while the active carbon is regenerated. SO_2 can be adsorbed and removed in the form of sulfuric acid (H_2SO_4) even if NH_3 is not injected in the desulfurization tower. However, since the following reaction with carbon occurs during desorption, consuming active carbon, NH_3 is added at the time of desulfurization to prevent such active carbon consumption.

$H_2SO_4 \rightarrow SO_3+H_2O$

$SO_3+0.5C \rightarrow SO_2+CO_2$

Coal is used to reduce desorbed SO_2 into elemental sulfur at 900°C for recovery. There is another method that oxidizes SO_2 into SO_3 to recover it as sulfuric acid.

During the development of this technology, carried out at J-POWER's Matsushima thermal power plant, first, an active-carbon desulfurization method (with an adsorption tower) that can treat 300Km^{3}N/h (90MW-equivalent) of gas was subjected to verification tests (1983-1986), obtaining removal efficiency of 98% for SOx and 30% for NOx. To improve the DeNOx removal efficiency, a combined desulfurization DeNOx pilot plant that can treat 3,000m^{3}N/h of gas with two towers was tested (1984-1986). SOx was almost completely removed by the desulfurization tower in the first stage, while 80% of NOx was removed. This technology, verified after being up-scaled to a capacity of 150Km^{3}N/h, was introduced in 1995 to the DeNOx unit of the No. 2 unit of the Takehara coal thermal power plant's normal-pressure fluidized-bed boiler (350MW), and is currently in operation. This technology was also installed as a desulfurizer in 2002 at J-POWER's Isogo thermal power plant's No. 1 new unit (600MW) (Photo 1). Although this technology is currently in operation, there are no cases of it being used as a combined desulfurization-denitration system.

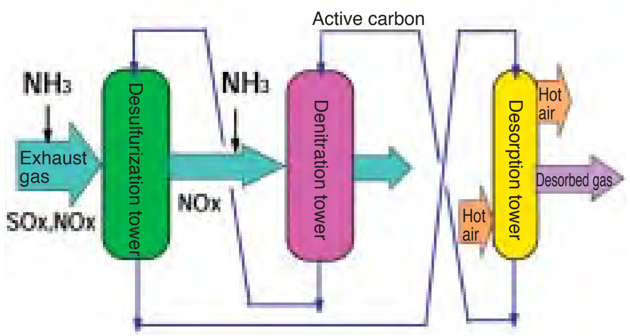

Fig. 1 Active carbon method desulfurization process

Photo 1 Active carbon method desulfurizer

(2) Electron beam process

Research and development: Ebara Corporation; Chubu Electric Power Co., Inc.; Japan Atomic Energy Research Institute; others

Project type: Voluntary

Overview

The electron beam process, as shown in Figure 2, involves using an electron beam to irradiate SOx/NOx in exhaust gas and injected NH_3 to cause a reaction for their recovery as ammonium sulfate ($(NH_4)_2SO_4$) or ammonium nitrate (NH_4NO_3) in the downstream precipitator. Byproducts: ammonium sulfate and ammonium nitrate, which are used as fertilizers. Removal efficiencies of 98% or more for SOx and 80% for NOx, at an NH_3/NO molar ratio of 1, is obtained at 70-120°C. The NOx removal efficiency also characteristically increases with higher SO_2 concentrations, though SOx removal efficiency does not affect the concentration of SO_2 at the inlet.

For this process, technology development was undertaken by Ebara Corporation and U.S. partners, including DOE, which made joint contributions from 1981-1987. In Japan, based on the development results, a pilot plant that can treat 12,000m^{3}N/h of gas was built at Chubu Electric Power's Shin-Nagoya power plant, where the technology was verified from 1991-1994.

Regarding this technology, a plant that can treat 300Km^{3}N/h (90MW) of gas (Photo 2) was built at Chengdu Heat-Electricity Factory, a co-generation power plant in Sichuan Province, China. It is currently being operated for demonstration and is obtaining a NOx removal efficiency of 80%.

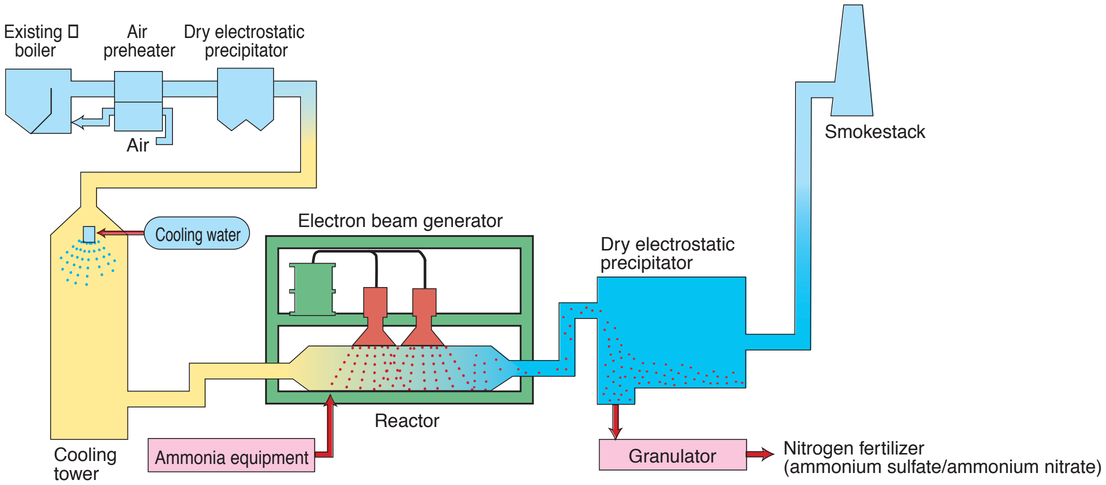

Fig. 2 Process flow for electron beam desulfurization process

Photo 2 Electron beam desulfurizer

References

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5B4. Particulate Treatment Technology and Trace Element Removal Technology

Technology overview

1. Background

Like NOx, emissions of particulate matter are regulated, with acceptable concentration levels set according to the type of fuel and size of boiler. At present, however, some regions are subject to a "total amount control," which provides for a region-wide overall emissions level as is the case with sulfur and nitrogen oxides. To comply with the regulations, the world's first electrostatic precipitator was employed in a Yokosuka thermal power plant in 1966 and many other thermal power plants have followed suit. To improve power generation efficiency, the development of pressurized-bed combustion and coal gasification combined-cycle technologies that use cyclones and ceramic/metal precision-removal filters is underway.

On the other hand, trace element control is now being intensified, such as through the addition of boron (B) and selenium (Se) to the regulated wastewater materials, and through the application of U.S. regulations for mercury (Hg).

2. Technology

(1) Electrostatic precipitators

Research and development:

Mitsubishi Heavy Industries, Ltd.; Hitachi, Ltd.; Sumitomo Heavy Industries, Ltd.; others

Overview

Electrostatic precipitators remove particulate matter in exhaust gas in accordance with the theory that dust charged by a negative corona at a discharge electrode adheres to a positive dust-collecting electrode.

The particulate matter that adheres to the electrode is removed and falls when the cathode is tapped with a hammering device. The effectiveness of the dust removal depends upon the electrical resistance of the particulate matter, and is most effective in an electrical resistivity range of particles 10^4-10^{11}Ω•cm in size. Pulverized coal, where the thermal electrical resistance of many particles is high, requires various countermeasures be taken against such particles.

One such measure involves adjusting the temperature conditions for dust collection; electrical resistance changes are shown in Figure 2. Those successfully developed and commercialized based on such characteristics are a high-temperature electrostatic precipitator operated at 350°C, a higher temperature than that of conventional low-temperature electrostatic precipitators (130-150°C), in order to lower the electrical resistance, and an advanced low-temperature electrostatic precipitator, with its electrical resistance lowered by operating it at a dew point or lower temperature of 90-100°C. Other than these, successful commercialized technology includes a moving electrode method, which brushes off particulate matter by moving the electrode to prevent back corona due to dust accumulation at the electrode, and a semi-wet electrostatic precipitator where a liquid membrane is applied to wash away dust. Other methods are commercialized electric discharge technologies, including an intermittent charge system to supply a pulsed voltage of several milliseconds, and a pulse charging system for several tens of microseconds.

At present, leading pulverized coal-fired plants built in and after 1990 employ very low-temperature electrostatic dust collection processes that can treat particulate matter with various properties and shapes.

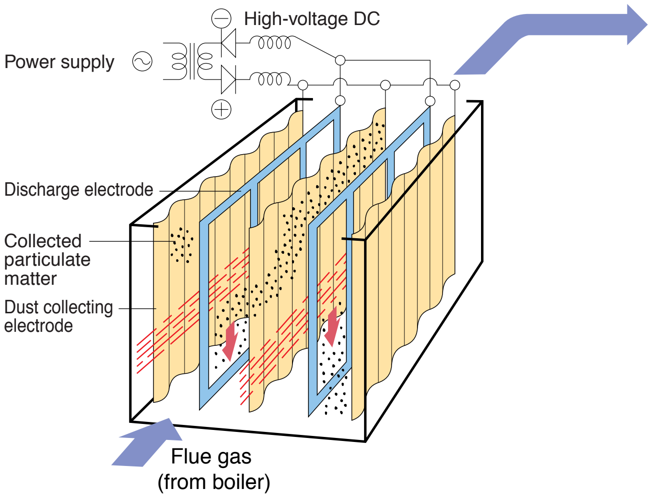

Fig. 1 Theory behind electrostatic precipitator

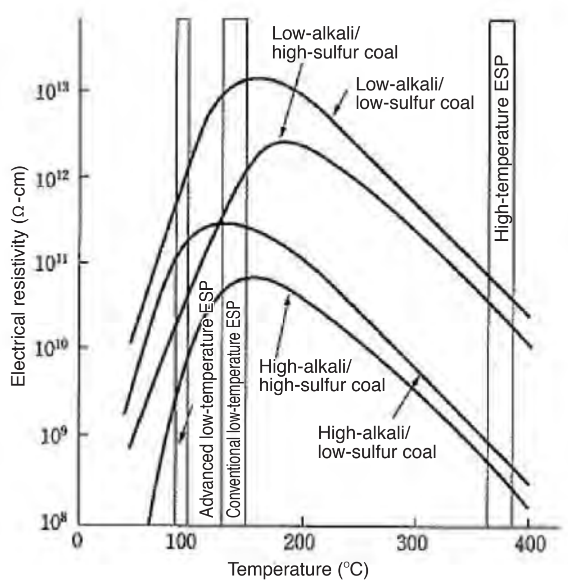

Fig. 2 Temperature effects on electrical resistance of coal ash

(2) High-temperature dust collection method

Research and development: Mitsubishi Heavy Industries, Ltd.; Hitachi, Ltd.; Kawasaki Heavy Industries Co., Ltd.; others

Overview

The high-temperature dust collection method is under development as a technology to remove particulate matter from hot gas for pressurized-bed combustion and integrated gasification combined-cycle (IGCC) power generation processes. This technology utilizes a multi-cyclone, a ceramic- or metal-based filter and a granular-bed method using silica or mullite to remove particulate matter. Multiple cyclones are mainly used for coarse, imprecise removal. Those used for precision removal include ceramic or metal filters of a cylindrical porous body into which SiC and other inorganic materials and iron-aluminum alloys are formed (Photo 1). The filters used for this method were developed by Nihon Garasu Kogyo or overseas by Paul Schumacher. Such technologies, now under durability evaluation/demonstration, are used for pressurized-bed combustion power generation at Hokkaido Electric Power's Tomatoh-Atsuma thermal power plant, with their verification tests conducted not only for IGCC at 200-tons/day at the Nakoso IGCC pilot plant but also under the EAGLE project. These technologies are also expected to be used at a 250MW IGCC demonstration unit slated for initial operation in 2007.

Photo 1 SiC ceramic filter

(3) Trace element removal method

Research and development: Japan Coal Energy Center

Project type: Subsidized coal production/utilization technology promotion project

Overview

Among the trace elements of coal, mercury is cited as the material released into the atmosphere at the highest rate, and approximately 30% of the mercury not removed by the precipitators/desulfurizers is thought to be released. However, nearly all bivalent mercury (Hg^{2+}) is removed, leaving behind nonvalent mercury (Hg) as the discharge matter. A method to remove this nonvalent mercury is being actively reviewed. The Japan Coal Energy Center, though still in the process of basic research, selected active carbon, natural inorganic minerals, and limestone as materials that can absorb mercury. Their absorption characteristics are now being evaluated. The research results prove that if a method to inject active carbon or an FCC ash catalyst into the flue for the removal of metal/mercury is combined with removal at the flue gas desulfurizer, 90% or more of the mercury can be easily removed.

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2) Sato, "Design and Actual Operations of High-Temperature Electrostatic Precipitators," Thermal/Nuclear, Vol. 34, No. 4, 1983.
3) Tsuchiya et al., "Technology Development of Low Low-Temperature EP in Coal Thermal-Purpose High-Performance Flue Gas Treatment System," MHI Technical Journal Vol. 34, No. 3, 1997.
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5) Coal-Based Next-Generation Technology Development Survey/Environment-Friendly Coal Combustion Technology Field (Trace Element Measurement/Removal Technology), NEDO results report, 2003.

5B5. Gas Cleaning Technology

Technology overview

1. Background

For the development of coal gasification gas-based power generation and fuel synthesis technologies, it is necessary to remove sulfur compounds (H_2S, COS), halides (HCl, HF), and other gas contents. As shown in Figure 1, a key application of this technology is found in the wet gas purification process that, after removing water-soluble halides and other contents with a water scrubber, desulfurizes the gas with a methyldiethylamine (MDEA) or other amine-based liquid absorbent for gas purification. This method, however, requires the gas to be cooled to around room temperature, thus losing much heat. Furthermore, the process becomes complex since it requires not only a heat exchanger but also a catalyst that converts hard-to-remove COS into H_2S. It is also difficult to precisely reduce sulfur compounds to a 1-ppm level.

To solve problems relating to the wet gas purification process, efforts are now underway to develop dry gas purification technology that purifies hot coal gasification gas as it is.

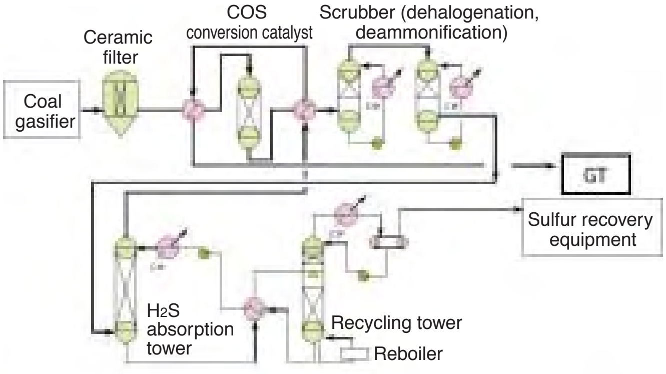

Fig. 1 Wet gas purification process

2. Technology

(1) Dry desulfurization method

Research and development: Japan Coal Energy Center; IGCC Research Association; Central Research Institute of Electric Power Industry; Kawasaki Heavy Industries, Ltd.; Ishikawajima-Harima Heavy Industries Co., Ltd.; Mitsubishi Heavy Industries, Ltd.

Project type: Entrained bed coal gasification power generation plant, etc.

Overview

As shown in Figure 2, in the dry desulfurization process, metal oxides are reduced by coal gasification gas, and the reduced metal oxides remove sulfur compounds from the gas, and are then converted to sulfides. This method can be used more than once by letting the sulfides react with oxygen to release the sulfur contents as SO_2 to return them to metal oxides.

The development of this process as a technology for integrated gasification combined-cycle power generation (IGCC) was promoted, with a target of reducing sulfur oxides to 100ppm or less in a temperature range of 400-500°C, where economical carbon steel can be used for piping. Iron oxide was selected as the metal oxide to be used and Ishikawajima-Harima Heavy Industries Co., Ltd. built a fluidized-bed desulfurization pilot plant (Fig. 3) that can treat all of the coal gas, using 100-200-μm iron ore particles. It was verified in the 200-ton/day Nakoso IGCC pilot plant (1991-1995). The Central Research Institute of Electric Power Industry and Mitsubishi Heavy Industries, Ltd., with an eye to applications in the fixed-bed desulfurization systems (Fig. 4), have jointly developed an iron oxide-based honeycomb desulfurization agent. They also built, under the 200-ton/day Nakoso IGCC pilot plant project (for coal gas production of 43,600m^3N/h), a pilot plant that can treat one-tenth of the amount of coal gas produced. The performance of the honeycomb desulfurization agent is being verified. Meanwhile, Kawasaki Heavy Industries, Ltd. has developed an iron oxide-based highly wear-resistant granular desulfurization agent for use in a moving-bed combined-desulfurization/dust collection system (Fig. 5) and evaluated its performance in a pilot plant capable of treating one-fortieth of the coal gas produced by the the 200-ton/day Nakoso pilot plant. This indicates that technologies for IGCC have already reached a validation stage.

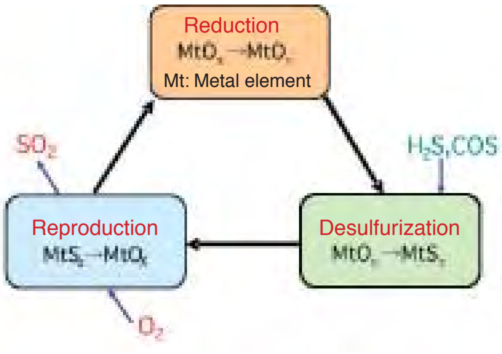

Fig. 2 Desulfurization reaction cycle

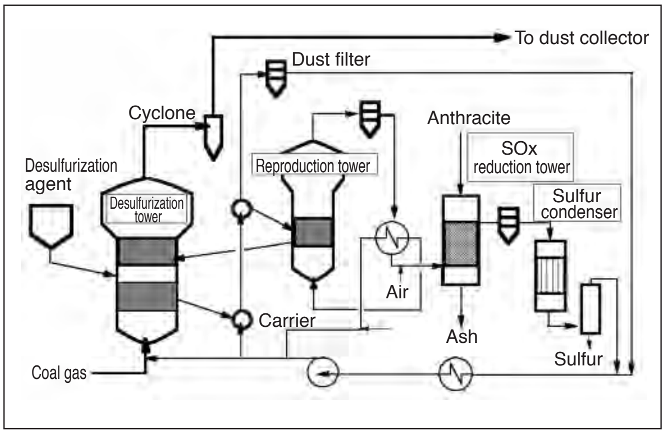

Fig. 3 Fluidized-bed desulfurization process

At present, a desulfurization agent that can reduce sulfur compounds to a level of 1ppm is under development for use in such applications as molten carbonate fuel cells, solid oxide fuel cells, and fuel synthesis. At the Central Research Institute of Electric Power Industry (CRIEPI), a desulfurization agent using zinc ferrite ($ZnFe_2O_4$), a double oxide of iron and zinc, has been developed and found capable of reducing sulfur compounds to 1ppm or less. It is now at the stage of real-gas validation. In addition, efforts to introduce the desulfurization agent into air-blown entrained-bed gasification systems have been made. Another important subject is the application of the agent to oxygen-blown gasification gas with a high carbon-monoxide concentration, which degrades the desulfurization agent by allowing carbon to be separated out of it.

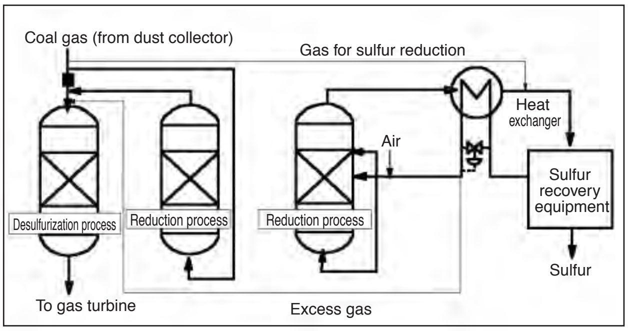

Fig. 4 Fixed-bed desulfurization process

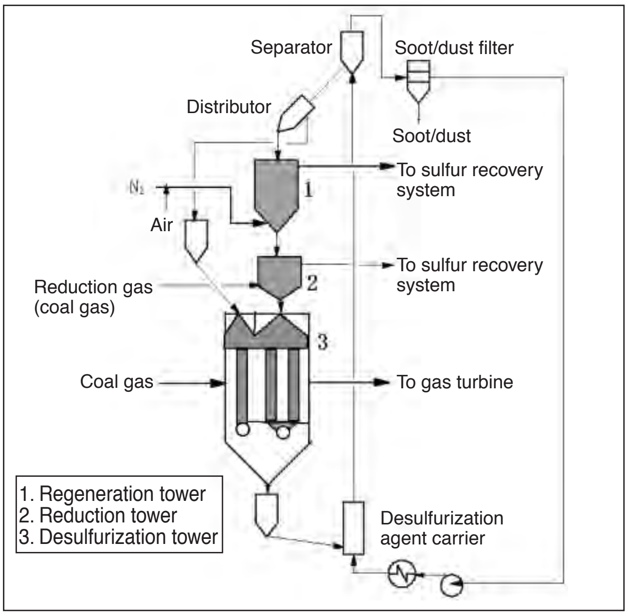

Fig. 5 Moving-bed combined dust collection-desulfurization process

(2) Dry dehalogenation method

Research and development: Central Research Institute of Electric Power Industry
Project type: Voluntary

Overview

To use coal gasification gas in molten carbonate/solid oxide fuel cells and for fuel synthesis, it is necessary to remove not only soot, dust and sulfur compounds but also halogen compounds.

For these applications, efforts are underway to develop a halide absorption agent capable of reducing halogen to 1ppm or less. At present, a method to remove HCl/HF from gas as NaCl/NaF using a sodic compound is under development. CRIEPI developed and tested a sodium aluminate ($NaAlO_2$)-based absorbent, confirming a possible reduction to 1ppm or less, but such efforts still remain on a laboratory scale as well as at a development stage. This method faces an important problem of how the absorbent should be reproduced or recycled.

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5C1. Coal Ash Generation Process and Application Fields

Technology overview

1. Background and general status of generation process

Coal ash has, since it was commercialized as a cement admixture in the first half of the 1950's, been widely used in applications such as a raw material for cement, cement mixtures, roadbed material, backfilling material, and embankment material, finding its way mostly into the cement sector, particularly, as a clay-alternative raw material for cement.

Coal combustion methods are roughly divided as follows:
(1) Pulverized coal combustion (dry-type)
(2) Stoker firing
(3) Fluidized-bed combustion
(4) Circulating fluidized-bed combustion

2. Generation rate

According to a survey conducted by the Center for Coal Utilization in 2003, the coal ash generation rate in Japan was 9.87 million tons a year, up 6.8%, or 630,000 tons, from the preceding year. Most coal-fired boilers for the electric utility industry are combusting pulverized coal. In addition, in general industries, 132 One-MW or larger coal-fired boilers are in operation, a majority of which combust pulverized coal. In terms of boiler capacity (steam generation rate), 50-ton/hr or smaller boilers are mostly of a stoker combustion type while many of the 100-ton/hr or larger boilers combust pulverized coal. Figure 2 shows changes in the rate of coal ash utilization and generation from electric power utilities and One-MW or larger installed power generation plants in general industries from 1993 through 2003.

3. Composition of coal ash

In Japan, 90% or more of the coal ash generated is from pulverized coal combustion, dwarfing the 7% or so from fluidized-bed and some 1-2% from stoker combustion. The generation ratio of fly ash to clinker ash (bottom ash) is 9:1.

As for the shape of coal ash particles, low-melting point ash is often globular while much of high-melting-point ash is indeterminate in shape. The average grain size of fly ash from pulverized coal combustion is approximately 25μm, similar to silt in fineness, between finer clay and coarser fine-grained sand for use as a soil material.

The chemical composition resembles mountain soil, with two inorganic components, silica (SiO_2) and alumina (Al_2O_3), comprising 70-80% of the total composition. Other than these, ferric oxide (Fe_2O_3), magnesium oxide (MgO), and calcium oxide (CaO) are also contained in slight amounts. In Japan, the composition of coal varies widely since 100 or more varieties of coal are imported from all over the world.

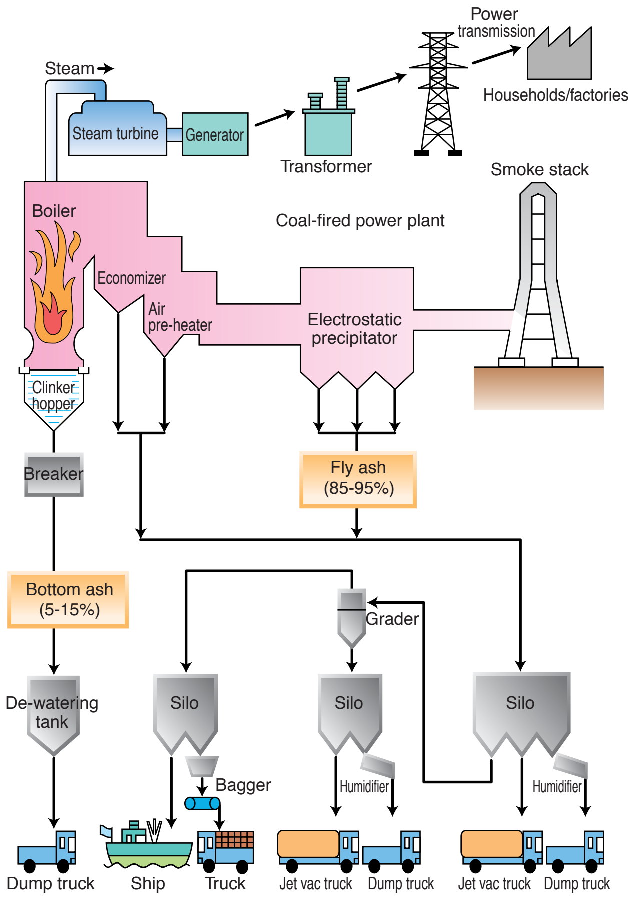


Fig. 1 Coal ash generation from a pulverized coal-fired boiler
Source: Japan Fly Ash Association

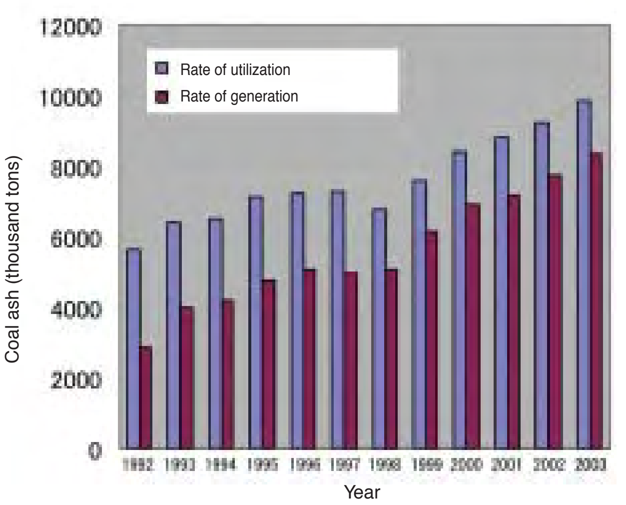


Fig. 2 Changes in coal ash generation and utilization rates

4. Application fields

Table 1 shows the effective utilization of coal ash in FY2003 by field. Usage in the cement industry is increasing annually. Of the 8.38 million tons used, the cement industry accounted for 6.33 million tons, or 75.5%. Recently, however, cement production has been declining and the prospects for substantial future increases are not bright. To cope with a likely increase in coal ash in the future, expanding utilization in other sectors will be important. In particular, the civil engineering field is expected to use more coal ash because of its high potential for consuming large quantities.

Table 1 Breakdown of fields for the effective use of coal ash (2003)

(Unit: thousand tons)

Total		Electric utilities		General industry		Total	
Field	Application	Rate of utilization	Composition ratio (%)	Rate of utilization	Composition ratio (%)	Rate of utilization	Composition ratio (%)
Cement	Cement raw material	4,354	71.32	1,522	66.90	5,876	70.12
	Cement mixture	149	2.44	159	6.99	308	3.68
	Cement admixture	95	1.56	48	2.11	143	1.71
	Sub-total	4,598	75.32	1,729	76.00	6,327	75.50
Civil engineering	Foundation improving material	138	2.26	104	4.57	242	2.89
	Civil work	103	1.69	25	1.10	128	1.53
	Power supply construction	79	1.29	0	0.00	79	0.94
	Roadbed material	50	0.82	110	4.84	160	1.91
	Asphalt/filler material	9	0.15	0	0.00	9	0.11
	Coal mine filling material	204	3.34	0	0.00	204	2.43
	Sub-total	583	9.55	239	10.51	822	9.81
Construction	Construction materials (boards)	213	3.49	164	7.21	377	4.50
	Artificial light-weight aggregate	0	0.00	0	0.00	0	0.00
	Secondary concrete product	18	0.29	1	0.04	19	0.23
	Sub-total	231	3.78	165	7.25	396	4.73
Agriculture/ forestry/fisheries	Fertilizer (including snow melting agent)	53	0.87	26	1.14	79	0.94
	Soil conditioner	11	0.18	82	3.60	93	1.11
	Sub-total	64	1.05	108	4.75	172	2.05
Others	Sewage treatment agent	4	0.07	1	0.04	5	0.06
	Steel making	13	0.21	8	0.35	21	0.25
	Others	612	10.02	25	1.10	637	7.60
	Sub-total	629	10.30	34	1.49	663	7.91
Total		6,105	100.00	2,275	100.00	8,380	100.00

References

1) The Center for Coal Utilization, Japan (now known as JCOAL): National Coal Ash Fact-Finding Survey Report (2003 results), 2005.
2) Environmental Technology Association/the Japan Fly Ash Association Coal Ash Handbook 2000 Edition, 2000.
3) Nobumichi Hosoda: CCUJ, Coal Ash Utilization Symposium lecture collection, 1998.
4) Natural Resources and Fuel Department, the Agency for Natural Resources and Energy: Coal Note (2003 edition), 2003.

5C2. Effective Use of Ash in Cement/Concrete

Technology overview

1. Technology overview

Research has been conducted on utilizing fly ash in the cement sector as an alternative for pozzolana. Enhanced research on the use of fly ash as a good-quality alternative to pozzolana led to its first application as a concrete admixture in the late-1940's, when it was used for structures like dams in the United States. This process was subsequently disseminated to other countries. In Japan, following its commercialization as a cement admixture early in the 1950's, standards were established for fly ash in 1958 and then for fly ash cement in 1960, encouraging its widespread application in general concrete structures.

In the meantime, fly ash came to be used as a clay-alternative raw material in cement in 1978 and by 2003, 70.1% of all the effectively used fly ash was used in this manner.

2. Utilization in the cement sector

1) Utilization as a clay-alternative raw material in cement

The raw materials for cement are limestone, clay, silica, and ferric oxide, with clay accounting for 15% of the total composition. Coal ash containing silica (SiO_2) and alumina (Al_2O_3) is also used as an alternative to clay. However, coal ash contains less SiO_2 and more Al_2O_3 than clay, which requires that more silica be used to offset the shortage of SiO_2. This deficiency limits the substitutability of coal ash for clay. At present, coal ash can constitute approximately 5% of the raw materials for cement but theoretically its use could be as high as around 10%.

2) Utilization as cement mixture

Japanese Industrial Standards (JIS) specify standards for fly ash cement[2], allowing the mixture to range from 5-30%. In general, fly ash can also be used as a Portland cement mixture, blended at 5% or less.

3. Utilization in the concrete sector

1) Utilization as a concrete admixture

1. Dam concrete

In Japan, research on fly ash as a concrete admixture started around 1950, with favorable results and economics through the first commercial use at a dam site in 1953.

Roller compacted dam-concrete (RCD) is a concrete product finished by compacting concrete of ultra-thick consistency with a vibration roller. The then Ministry of Construction led independent technology development to utilize this in a concrete dam, successfully systematizing the trial into the RCD construction method, which was commercialized for dam construction in 1978.

In order to prevent cracks, dam concrete is generally not allowed to reach high temperatures.

Due to this restriction for RCD, only a portion of the cement can be replaced by fly ash in order to limit temperature increases. Generally, the replacement ratio is 20-30%. As many as some 30 dams have thus far been built employing this construction method, making it a well-established engineering method, justifying the development efforts.

2. Pre-packed concrete

Pre-packed concrete is a concrete product fabricated by casting coarse aggregate of a designated grain size into a mold or place of application beforehand and injecting mortar into voids at an appropriate pressure. The mortar used must be one of high fluidity, with little material separation, and of moderate expansibility. For this purpose, fly ash is generally mixed at a rate of 25-50%.

Applications include underwater concrete, mass concrete, and the repair/reinforcement of existing concrete work. The substructure work for the Honshu-Shikoku Bridge also employed this construction method.

3. High-fluidity concrete

Fly ash enriched concrete (FEC) is a two component-type, high-fluidity concrete product using cement and fly ash as powder materials. It can contain 40% or more fly ash, providing such characteristics as excellent self-filling capability requiring no compaction after casting, minimal cracking due to heat of hydration, which increases its long-term strength, as well as higher durability against alkali aggregate reactions and salt/acid damage.

Fly ash and slag concrete (FS), using steel slag and coal ash as aggregates, is a plain concrete product developed for wave-breaker superstructure works and fixation blocks/tetrapods that do not require great strength.

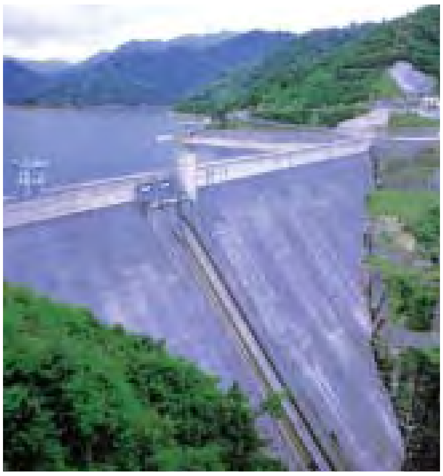
4. Industrial standards for concrete-purpose fly ash

After evaluating fly ash as a concrete admixture it was determined that it performed well due to its ultra-fineness and the limited quantity of unburned carbon. Subsequently, ultra-fine items produced by an advanced analyzer were commercialized. In addition, items with higher-performance qualities, or qualities likely to prove effective as admixture despite their substandard state, were added to the JIS standards[3] and classified as grade 4 materials, thereby designating them with a quality suitable for utilization. Grade 1 fine fly ash is used as an admixture for concrete products used as water/moisture barriers. It must be durable, among other characteristics. Uses include ocean concrete and specially-reinforced shielding material used for long-distanced pumping.

Table 1 Quality of fly ash (JIS-A 6201)

Class		Class I fly ash	Class II fly ash	Class III fly ash	Class IV fly ash
Silica dioxide (%)		45.0 or higher			
Moisture content (%)		1.0 or less			
Ignition loss[1](%)		3.0 or less	5.0 or less	8.0 or less	5.0 or less
Density (g/cm^3)		1.95 or higher			
Fineness[2]	Residue on 45 μm sieve (screen sieve method) [3] (%)	10 or less	40 or less	40 or less	70 or less
	Specific surface area (Blaine method) (cm^2/g)	5000 or higher	2500 or higher	2500 or higher	1500 or higher
Flow value ratio (%)		105 or higher	95 or higher	85 or higher	75 or higher
Activity index (%)	Material age: 28 days	90 or higher	80 or higher	80 or higher	60 or higher
	Material age: 91 days	100 or higher	90 or higher	90 or higher	70 or higher

1. In place of ignition loss, the unburned carbon content ratio may be measured by the method specified in JIS M 8819 or JIS R 1603 to apply to the result a stipulated value of ignition loss.
2. Fineness based on the screen sieve method or the Blaine method.
3. Regarding fineness, the results of the Blaine method are provided as a reference value for the screen sieve method.


Application for dams


Application for buildings

References

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2) JIS R 5213-1997, 1997.
3) JIS A 6201-1999, 1999.

5C3. Effective Use of Ash in Civil Engineering/Construction and Other Applications

Technology overview

1. Technology overview

Outside of its application in concrete, coal ash is widely used in the civil engineering sector for road construction, foundation improvements, back-filling, or for use in other earthwork and in the construction sector as an artificial light-weight aggregate. On the other hand, in the agriculture/forestry/fisheries sector, it is used as a fertilizer or soil conditioner.

To cope with the anticipated increase in the generation of coal ash in the future due to such factors as the construction of new coal-fired power plants, utilization technologies are now under active development out of the necessity to expand the utilization of coal ash in the above-mentioned sectors. In order to accomplish this, several challenges, including the diffusion of technology, the exploitation of demand, and the improvement of the distribution mechanism, must be addressed.

2. Utilization for civil engineering

1. Road construction material

The "Outline of Asphalt Pavement"[1] allows fly ash to be used as an asphalt filler material, and clinker ash as a lower subbase material, frost heave depressant, and barrier material.

Fly ash can be used for the upper/lower subbase and subgrade. A cement stabilization treatment construction method adds fly ash to cement to be treated under moderate moisture content for application. This construction method strengthens quickly and is stable over the long-term. Another technology[2,3,4,5] has also been developed to process coal ash for use as a road construction material.

2. Earthwork material

Fly ash can be effectively used for an embankment or reinforcement material since it is lighter than common earthwork materials. In recent years, therefore, various technology development efforts[6,7,8] have been made, resulting in a number of applications. Among these is an application using fly ash in its original powder state with cement added as a solidifier to coal ash, as well as fly ash's utilization as a stabilizing material. It is also granulated or processed in other ways for different applications. Review is also underway for the intended commercialization of fly ash as a soil stabilizer or a construction sludge conditioner due to its pozzolanic activation as well as its self-hardening[9] property.

Meanwhile, basic research of the elution[10] of coal ash's trace elements is continuing since fly ash's use in earthwork must be in harmony with the environment.

Photo 1 Application for road construction

3. Utilization in the construction sector

1. Artificial light-weight aggregate

Development efforts[11,12] have successfully produced technology to pelletize/calcine coal ash and cement or the like into artificial light-weight aggregate. Demand, driven by urban development and high-rises, is expected to grow, making it important to further the technological development of artificial light-weight aggregate as well as to reduce production costs.

2. Others

The resemblance of coal ash's elements to the chemical composition of existing construction materials also allows it to be used as a clay-alternative raw material for ceramic products, such as clay roofing, bricks, and tiles, or as a cement mixture for boards (interior/exterior wall material for construction).

4. Utilization in the agricultural/forestry/fisheries sector

1. Fertilizer

Fly ash, from pulverized coal-combustion ash, was designated as a special fertilizer in 1960, as was clinker ash in 1992. Several thousands of tons a year of potassium silicate fertilizer, containing hard-to-dissolve silicic acid contained in coal ash, is also produced.

2. Soil conditioner

Clinker ash, whose chief components, SiO_2 and Al_2O_3, are almost the same as those of ordinary soil, is suitable for the growth of vegetables. Moreover, it is used to grow sod for golf courses or to improve the soil of poor-drainage areas or arable land since its countless spores retain water well, enabling fertilizers to be effective for a longer duration and, at the same time, its similarity in shape to sand provides comparable water permeability.

3. Utilization in the fisheries sector

There are long-established cases where coal ash has been used for fish breeding reefs and seaweed beds. A recent effort aims to use coal ash as a mounding material for a man-made undersea mountain range to cause artificial upwelling currents.[13]

Photo 2 Artificial aggregate fabricated from coal ash (Toughlite)

Photo 3 Application as fertilizer

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5C4. Technology to Recover Valuable Resources from Coal Ash

Technology overview

1. Technology overview

Various R&D activities are being conducted to identify and develop effective coal ash utilization technologies. Potential technical applications that have been studied include the recovery of valuable resources from coal ash through physical and chemical treatments, and the utilization of coal ash as a desulfurization agent, a rust inhibitor, and as an admixture and filler for polymeric materials (rubber and plastic). Through zeolitization, additional potential applications have been identified, including utilization as an adsorbent, a catalyst, an ion-exchanger, and a desiccant.

2. Valuable resource recovery

Coal ash contains valuable substances including cenosphere (hollow ash), magnetite silica, alumina, iron oxide, and titanium oxide, as well as trace amounts of other valuable metals.

1) Recovery of valuable resources through physical treatment

Magnetite recovery through magnetic separation

The recovery of magnetite (Fe_3O_4) from fly ash is performed prior to the chemical treatment process to recover valuable elements such as Si, Al, Ti, and Fe. Magnetite, recovered through a magnetic separation process, can be used, for example, as an alternative to a heavy separation medium.

2) Recovery of valuable resources through chemical treatment

(1) Direct hydrofluoric acid extraction method

An acid extraction method, which uses an acid mixture of hydrofluoric acid and hydrochloric acid, has been developed to recover valuable resources from fly ash. The SiO_2 recovered is characteristically of high purity (99.9% or higher) and fine particles (1μm or less).

(2) Calcination method

In the calcination method, calcium is combusted with fly ash to convert the acid-stable mullite present in the fly ash into acid-soluble anorthite or gehlenite, resulting in a high recovery rate of Al.

3. Artificial zeolite

Zeolite is a generic term for hydrated crystalline alumina silicate that, as one of its characteristics, has a porous structure and therefore a large specific surface area. It also contains ion-exchangeable cations and crystallization water that can be adsorbed/desorbed. Because of such characteristics, zeolite can be used, for example, as an adsorbent, a catalyst, or a desiccant[1].

Treating a coal ash-alkaline aqueous solution mixture[2] hydrothermally produces various kinds of zeolite, depending upon the reaction conditions.

The Clean Japan Center[3] conducted demonstration tests at a 10,000 ton/year-scale demonstration plant built for coal ash zeolite production in 1990. In this coal ash zeolite production process, coal ash zeolite is obtained when coal ash is boiled with sodium hydroxide and stirred. Solid contents are then separated, washed and dehydrated. The zeolite produced is of an Na-P type. Meanwhile, coal ash zeolite production processes commercialized to date are of a batch method, similar to non-coal ash processes, while flow-through continuous synthesis processes have also been developed[4]. In addition, applications that are expected to use a large volume of zeolite are now being reviewed, with an eye on reducing production costs and developing technology to synthesize zeolite in ways suitable to each application.

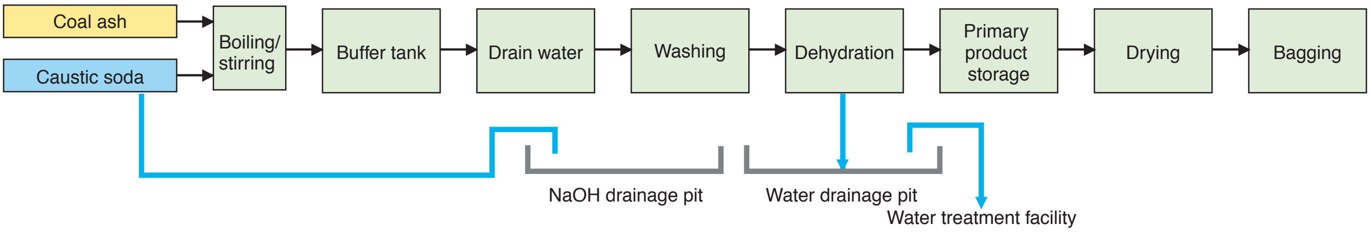


Fig. 1 Coal ash zeolite production process

4. Utilization in other sectors

1) Desulfurization agent

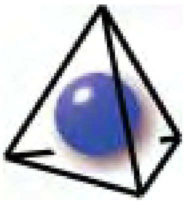
Dry desulfurization technology using coal ash has been commercialized, using a hardened mixture of coal ash, slack lime, and gypsum, which have excellent desulfurization capabilities.

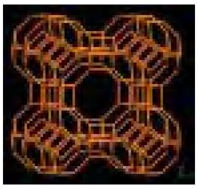
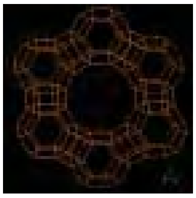
2) Admixture/filler for polymeric materials (including rubber and plastic)

Fly ash, since it is a collection of small, round glass-bead-like fine particles, is being studied for possible use as a rubber filler or as an alternative to plastic admixtures including calcium carbonate, silica, alumina, wood flour, and pulp.

3) Other

Other than the above, technology development is currently focused on coal ash characteristics-based applications, such as in an agent to prevent rust caused by oxidation in steel-making, as well as for use in water purification or for casting sand.



	Structure	Molecular formula	Pore size (Å)	Pore volume (cc/g)	CEC (meq/100g)
A		$Na_{12}[(AlO_2)_{12}(SiO_2)_{12}]\cdot 27H_2O$	Na type: 4 Ca type: 5	Na type: 0.3	548
P		$Na_6[(AlO_2)_6(SiO_2)_{10}]\cdot 15H_2O$	Na type: 2.6	Na type: 0.36	514 (The figure is large but the exchange rate is small.)
X		$Na_{86}[(AlO_2)_{86}(SiO_2)_{106}]\cdot 264H_2O$	Na type: 7.4	Na type: 0.24	473

Cation-containing aluminosilicate found in different forms for different structures/compositions, with each having its own characteristics and applications.

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6A1. Modeling and Simulation Technologies for Coal Gasification

Research and development: Japan Coal Energy Center
Project type: NEDO-commissioned project

Technology overview

1. Overview of basic technology for advanced coal utilization (BRAIN-C)

The consumption of fossil fuel impacts the environment in a variety of manners. There is also an impact on the environment during the coal production, transportation, and utilization processes. During utilization, in particular, coal dust, ash dust, acid gases (NOx, SOx), and carbon dioxide are discharged, raising concerns of what the unregulated consumption of coal may possibly have on the environment. However, technologies to minimize the harmful impact coal utilization has on the environment, collectively called clean coal technology (CCT), are in widespread use in developed countries, including Japan. Given this, the "Basic Technology Development Program for Advanced Coal Utilization (BRAIN-C)" is focused on coal gasification technology and the rapid commercialization of new high-efficiency and clean coal utilization technologies, such as coal gasification and pressurized fluidized-bed processes. Basic coal data, from a variety of perspectives, has also been collected and compiled. Numerical simulation is a very effective tool to predict the characteristics of a pilot or actual production unit by utilizing the above-mentioned basic data. On the other hand, it can also be used to evaluate and select useful basic data. With this taken into consideration, technology development under BRAIN-C has proceeded from the aspects of both useful basic data retrieval/storage as well as high-precision numerical simulation.

Figure 1 shows the "BRAIN-C technology map." Results from this project are roughly grouped into the following three categories:

(1) An entrained-flow gasification simulator
(2) A predicted model/parameter correlative equation
(3) A coal database

(1) to (3) above are illustrated below and each is as an integral part of the results from this project, indispensable for actual usage in a variety of situations. The appropriate utilization of each in accordance with the application allows for full optimization.

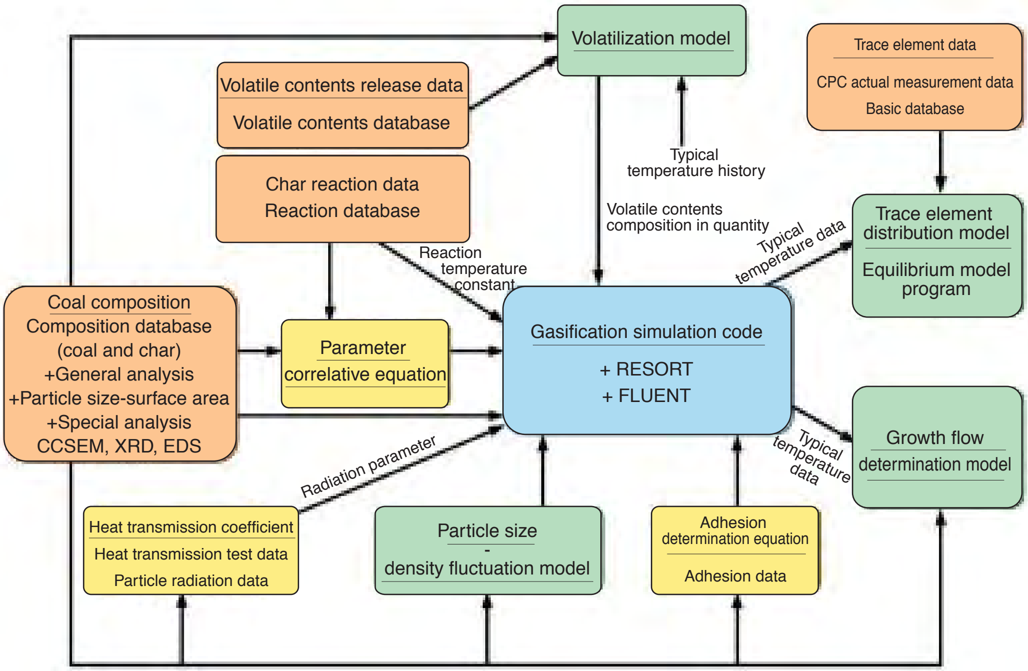

Fig. 1 BRAIN-C technology map

2. Entrained-flow gasification simulator

An entrained-flow gasification simulator, based on thermal fluid analysis software, computational fluid dynamics (CFD), and capable of simultaneously analyzing flow, reaction, and heat transmission, can calculate temperature distribution, ash adhesion locations, gas composition, etc., within a gasifier if given, as input data, such parameters as reactor shapes, operating conditions, coal properties and reaction data (Fig. 2). Highly reliable prediction results can be used for evaluating operating condition validity, reactor design, and other information in advance.

In the BRAIN-C program, the coal gasification reaction model shown in Figure 3 and the particle adhesion model shown in Figure 4 are built within CFD in order to establish technology for an entrained-flow gasification simulator. Simulation results are then compared with gasification furnace operating data in coal-based hydrogen production technology (HYCOL or EAGLE) to examine the validity.

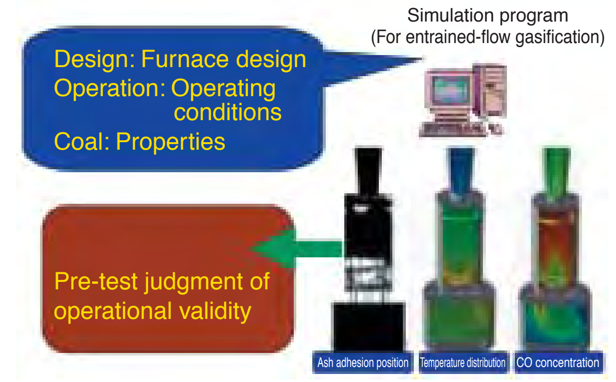

Fig. 2 Functions of entrained-flow gasification simulator

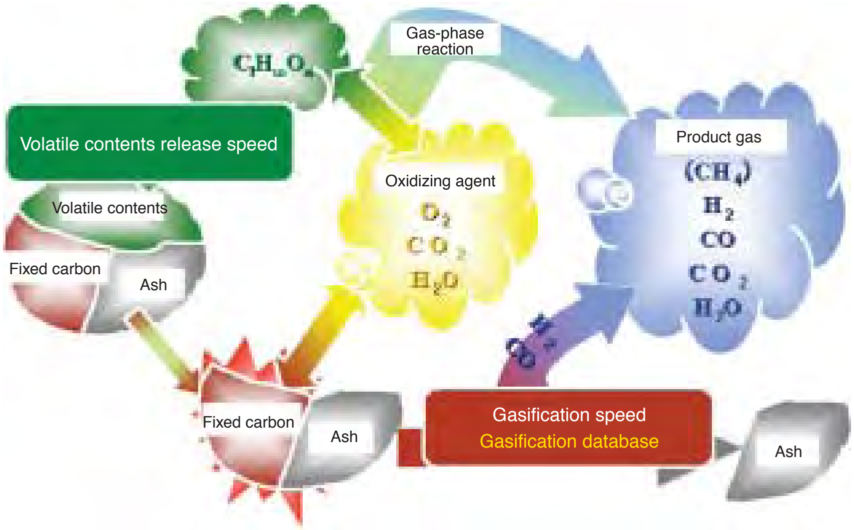

Fig. 3 Coal gasification process modeling

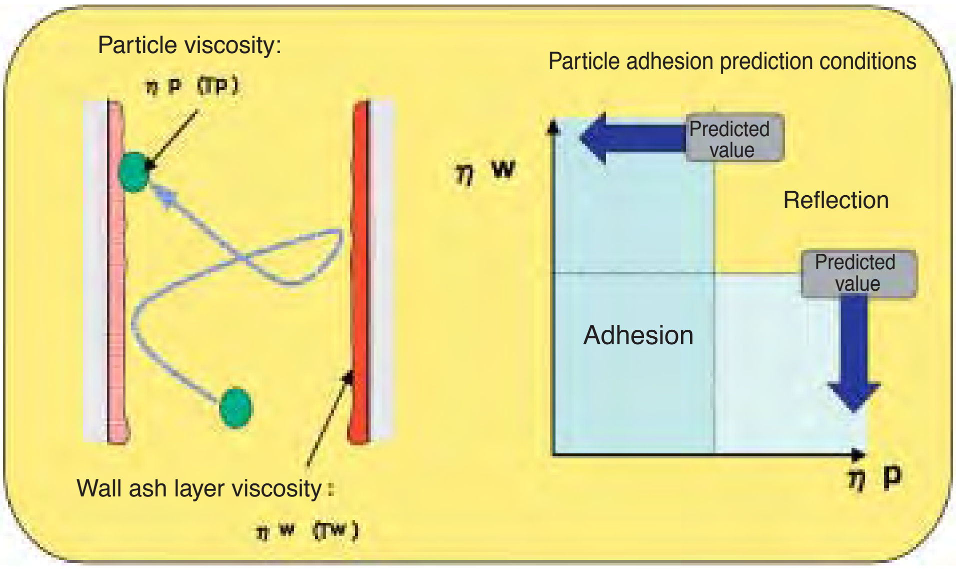

Fig. 4 Ash viscosity-based adhesion prediction model

Figure 5 shows an example of the comparative results between the formation position of a fused ash layer and the internal condition of a gasifier after operations. This showed that the formation position of the fused ash layer as predicted by the simulator corresponded well to the position where the fused ash layer actually existed, confirming the accuracy of the simulation relative to the actual data.

Figure 6 shows the result of case studies on HYCOL using a gasification simulation. The near-wall temperature and ash viscosity on the wall shown on the left side of Figure 6 are those reproduced by simulation after 1,000 hours of operation. The temperature of the bottom area of the furnace (shown in red in upper image) into which slag flows are high versus the low ash viscosity in the bottom area of the furnace (shown in blue in the lower image). The temperature of the upper part of the furnace is low (shown in green in upper image), providing conditions where particles can hardly adhere. On the other hand, the near-wall temperature and ash viscosity on the wall shown on the right side of Figure 6 are the result of simulation under intentionally modified operating conditions. For this case, the oxygen ratio at the top of the chart is higher and that at the bottom is lower than is shown on the right side of the figure. In such cases, it was found that the temperature at the bottom of the furnace decreases (shown in orange) and the low-ash-viscosity region (shown in blue) narrows while the upper part of the furnace becomes hot (the region in red increases) to form a region where it is easier for ash to adhere, categorized as less desirable operating conditions.

By using the gasification simulator in this manner, analysis can be easily made even if gasification conditions are altered. This has resulted in growing expectations for use of the simulator in future gasification projects.

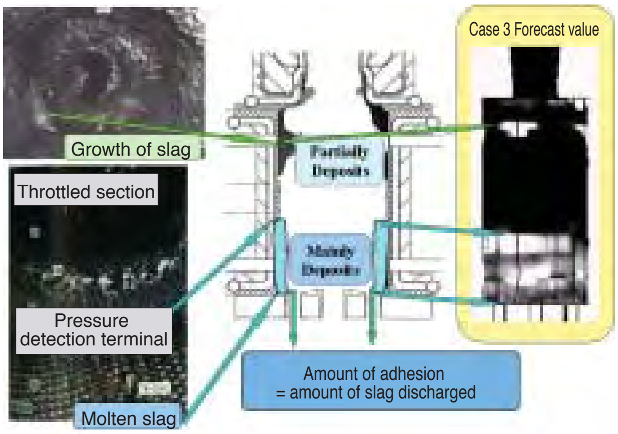

Fig. 5 Ash adhesion position verification results

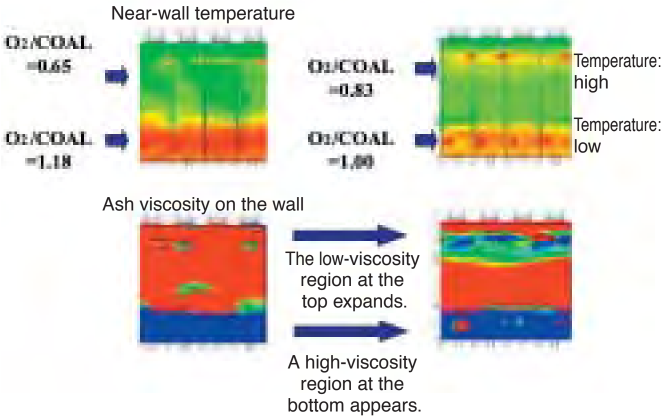

Fig. 6 Simulator-based studies

3. Predicted model/parameter correlative equation

The entrained-flow gasification simulator can be applied to various furnace designs and operating conditions, but it is not applicable to all types of coal. It is, therefore, necessary to input coal characteristics into the simulator by coal-type as a parameter. This parameter generally uses the data obtained from basic test equipment but, from the vantage of obtaining a prompt evaluation, it is desirable to establish a means to obtain the parameters from a general analysis of coal or from structural composition data (an advanced model incorporating correlative equations for estimations and experimental conditions). More specifically, a generalized volatilization model and the adhesion determination equation are among the tools to prepare parameters. In the meantime, a trace elements distribution model and an adhesion determination equation model offer determinations from simulation results, playing another important role. Under the BRAIN-C, therefore, prediction equations around a gasification simulator have also been developed so that the simulator can be used effectively and quickly.

4. Coal database

The development of a correlative equation or model indispensably requires physical and basic experiment data, including general analysis data. There is, however, a significant issue in that the characteristics of coal differ by lot, even if the coal has come from the same coal mine. It was, therefore, first necessary for each testing body that obtained physical and basic data to use exactly the same coal samples. Figure 7 shows a coal sample bank built within the National Institute of Advanced Industrial Science and Technology. Such unified management of analytical test samples has enabled the shipment of identical samples to all testing research bodies.

As far as the identical sample-based data is concerned, the measurement of typical data will be completed under this project for 100 types of coal for general/special analysis data, and for at least ten types of coal, depending upon the data criteria, for basic experiment data. Eventually, all of this measurement data will be compiled in an Internet-accessible coal database. Some of the data thus far obtained, as shown in Figure 8, has already been uploaded to JCOAL's server and is accessible or retrievable. Much of this data is stored in an easy-to-calculate/process Excel file (Fig. 9) and can also be downloaded.

Standard sample coal storage (AIST)

Standard sample coal (for delivery)

Fig. 7 Coal sample bank

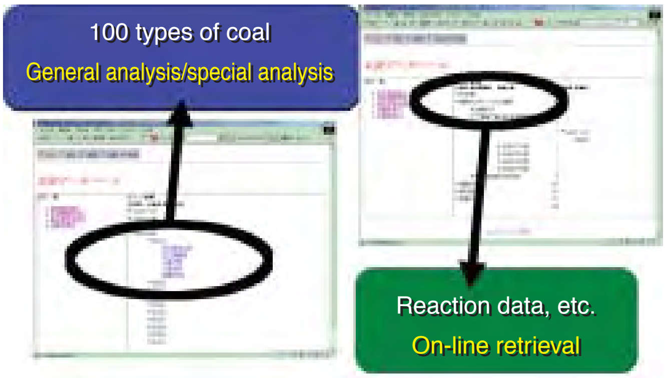

Fig. 8 Coal database

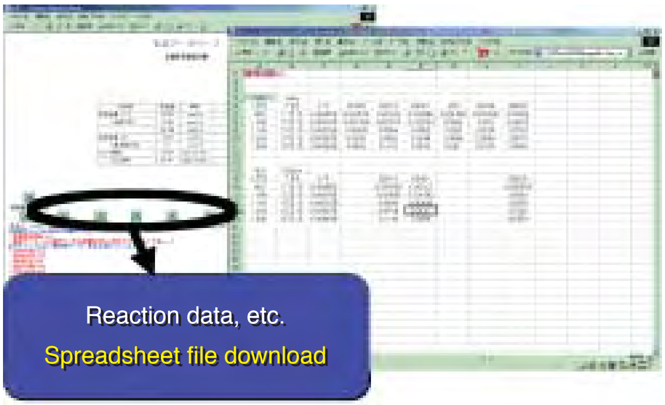

Fig. 9 Basic data acquisition

5. Dissemination of basic coal utilization technology products

An entrained-flow gasification simulator thus far developed under BRAIN-C is capable of making practical predictions through the utilization of various models and basic data. The BRAIN-C Project, finished in 2004, developed a well-equipped system to make a wide selection of programs and basic data available so that the products developed under this project could be used without limitation. Detailed service manuals, as well as workshops for the purpose of encouraging the optimal utilization of these products, were also being prepared.

Despite the predominance of coal gasification technology in this development project, other types of gasification projects are strongly encouraged to use the simulation code, since it can be widely used for combustion simulation as well as in other applications.

7A1. Co-generation Systems

Technology overview

1. Definition of co-generation

A co-generation system is a system using a common energy source to produce both electricity and thermal energy for other uses, resulting in increased fuel efficiency.

2. Co-generation systems

Co-generation systems are roughly divided into two types. One is a type that powers a diesel engine, gas engine, gas turbine, or other motor to generate power while recovering the waste heat from the motor as hot water or steam through a thermal exchange at a boiler. The other type involves generating power by rotating a steam turbine with steam produced by boilers and removing steam of a desired pressure as process steam.

The former generally uses liquid or gas fuel and is often small-scale for hotels, supermarkets, and hospitals.

As for the latter, every type of fuel, including coal, is used as fuel for boilers and many are found as relatively large-scale industrial-use thermal power plants. Systems are further grouped into ones that mainly supply electricity (condensing turbines) versus those that mainly provide steam (back-pressure turbines).

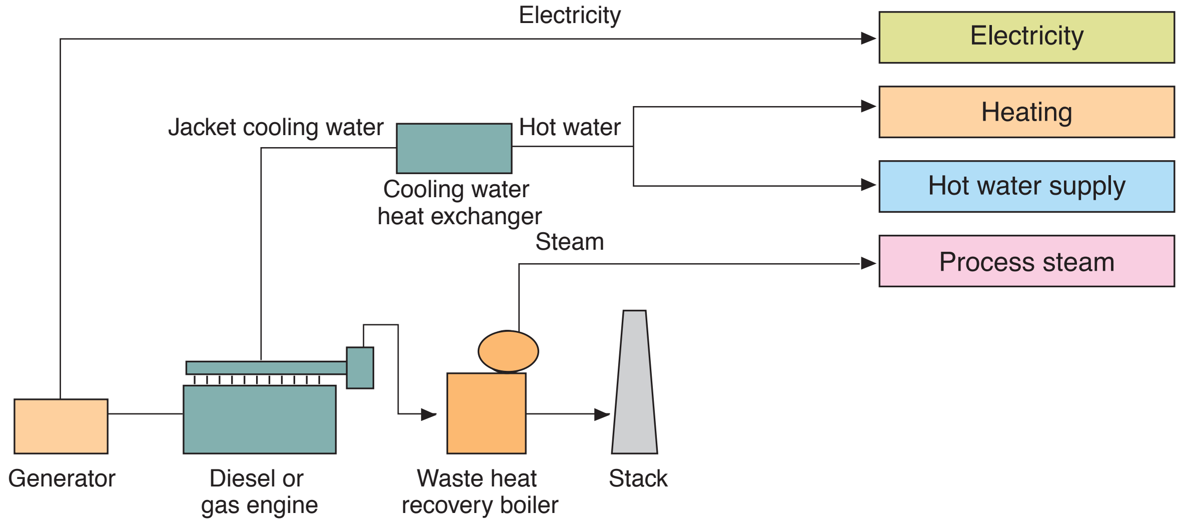

Fig. 1 Overview of a typical diesel/gas co-generation system

3. Efficiency

In general, the power generation efficiency of a coal thermal power generation plant producing only electricity is around 40%. On the other hand, the overall thermal efficiency of a cogeneration system, which combines power generation efficiency and heat recovery efficiency, depends upon whether its main purpose is to supply electricity or to supply heat. Co-generation systems that primarily supply heat can reach efficiency levels as high as 80%.

(1) Co-generation at a large-capacity coal thermal power plant

Kobe Steel's Shinko Kobe Power Station, a 1,400MW (700MW x 2 generators), large-scale coal thermal power plant, wholesales/supplies electricity as an independent power producer (IPP). Electricity generated from the No. 1 unit, which began operating in April 2002, and the No. 2 unit, which began operating in April 2004, are all being delivered to The Kansai Electric Power, Inc.

(2) Regional supply of heat

A portion of the steam from the Kobe plant to be used for power generation is extracted in order to supply up to a maximum of 40 tons/hr to four nearby sake-breweries. This amount, accounting for approximately 2% of the steam generated in the boilers, indicates that the share of heat supplied is small. Previously, each brewery had produced its own steam. Now, however, the power plant's secondary steam is extracted at the steam header and directly supplied to the breweries. By using steam extracted from the power plant, regional energy conservation efforts are realized.

(3) Heat supply conditions

Steam extracted from the turbine of the power plant contains trace amounts of a rust inhibitor called hydrazine and, therefore, cannot be directly supplied to breweries since the steam used in the breweries comes into direct contact with rice. Secondary steam, produced indirectly using a steam generator powered by turbine extraction steam (primary steam), is therefore supplied to breweries. An overview of Kobe Steel's Shinko Kobe Power Station is shown in Photo 1.

Photo 1 View of Kobe Steel's Shinko Kobe Power Station

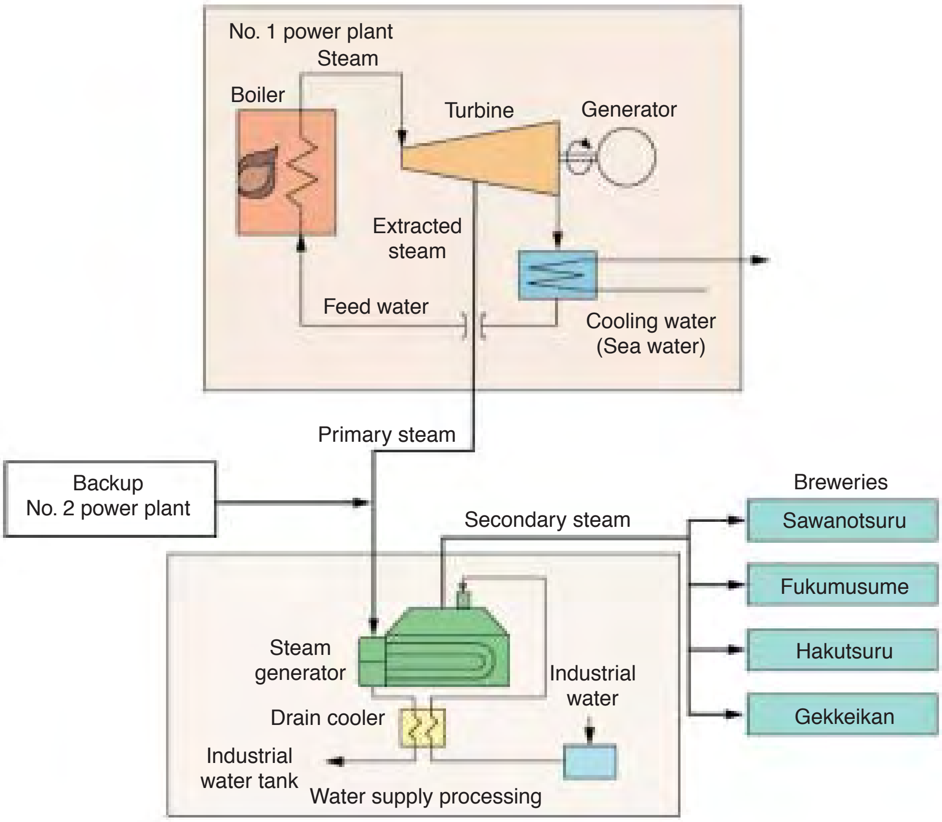

Fig. 2 Process flow of heat supply facility

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7A2. Co-production Systems

Technology overview

1. Feasibility of fuel co-production power generation systems

Conventional attempts to develop innovative processes within a single industry face limitations. To continue the reduction of CO_2 emissions, it is necessary to comprehensively review existing energy and material production systems and to develop technologies that optimize the individual processes and the interface between processes. This will not only improve the conversion efficiency and conserve energy, but will also fundamentally and systematically change energy and material production systems.

The "fuel co-production power generation system," which produces power, fuel, and chemicals from coal, improves the total energy use efficiency through the unification of industries through the construction of an industrial coal complex.

In the power, iron and steel, and chemical industries, where large amounts of coal are consumed to produce energy, structuring a core plant that produces energy and chemicals simultaneously, and assembling peripheral plants to produce various products, enhances the unification of industries centered on a core plant, thus forming an industrial coal complex based on a new material and energy production system. This unification of industries would advance existing industrial systems to a next-generation, hybrid industrial system.

The core technology for that type of fuel co-production power generation system is coal gasification technology. By combining a high-efficiency power generation system, such as IGFC, with a process to co-produce storable fuel, the normalization of the load to the gasification reactor and a significant reduction of CO_2 emissions are attained.

Furthermore, the waste heat in the industrial coal complex is utilized to recover chemicals from coal through endothermic reactions, thus further improving energy efficiency and enhancing the industrial coal complex.

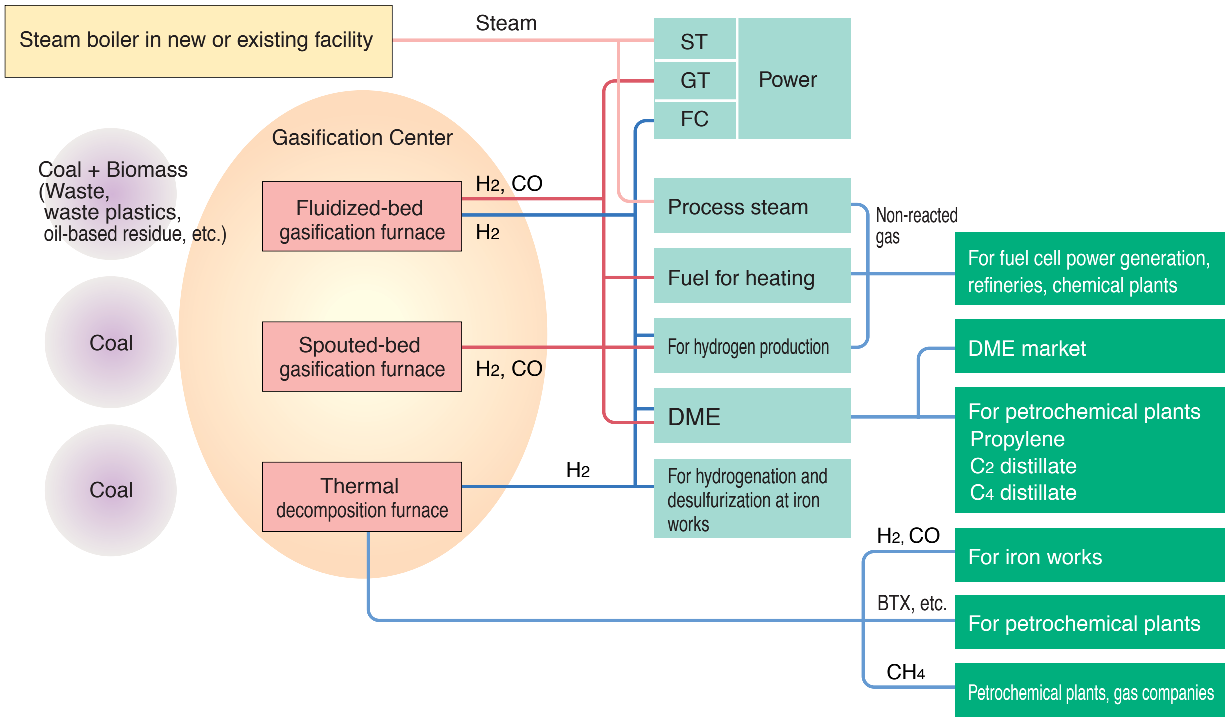


Fig. 1 Energy flow

2. Co-produced fuel and raw materials for chemicals

There are overseas examples of fuel and chemicals being co-produced along with power through coal gasification, with production varying depending on the needs of the related companies, like Sasol's production of synthetic fuel (GTL) in South Africa and Eastman Chemical Company's production of acetyl chemicals in the U.S. Other examples of chemical synthesis with coal gasification include the production of methanol and methane in China, Europe, and the U.S. It is anticipated that DME, which has applications as a raw material for clean fuel and for propylene production, will be produced as will hydrogen, for which demand is expected to increase for use as a fuel for fuel cells and for the coming hydrogen-oriented society.

Clean gas for iron works is also expected to be produced to respond to changes in the energy balance at iron works of the future.

3. Co-production systems

The co-production system produces both materials and energy to significantly reduce the exergy loss that occurs mainly in the combustion stage, and achieves an innovative and effective use of energy.

The co-production system is a new production system that combines aspects of the conventional system, which aims to improve energy conversion efficiencies, and the cogeneration system, which effectively uses the generated thermal energy to the maximum extent possible, but goes one step further by producing both energy and materials in order to significantly reduce their consumption. The co-production system, which should stimulate the economy, is also clean, thereby solving both energy issues and environmental concerns simultaneously. Consequently, co-production systems that produce energy, such as power and fuel, while also producing materials shall be encouraged from the perspectives of creating new energy markets and also creating new industries.

Coal co-production systems focused on coal gasification will be able to solve environmental issues through a significant reduction in CO_2 emissions by realizing the development of high grade and comprehensive coal utilization technology. That type of system technology development would trigger strong technological innovation in the coal utilization field, and vigorous innovation is expected to increase international competitiveness and encourage the structuring of a recycling-oriented society. Internationally, the development of co-production systems should be an important technological issue that addresses global environmental issues.

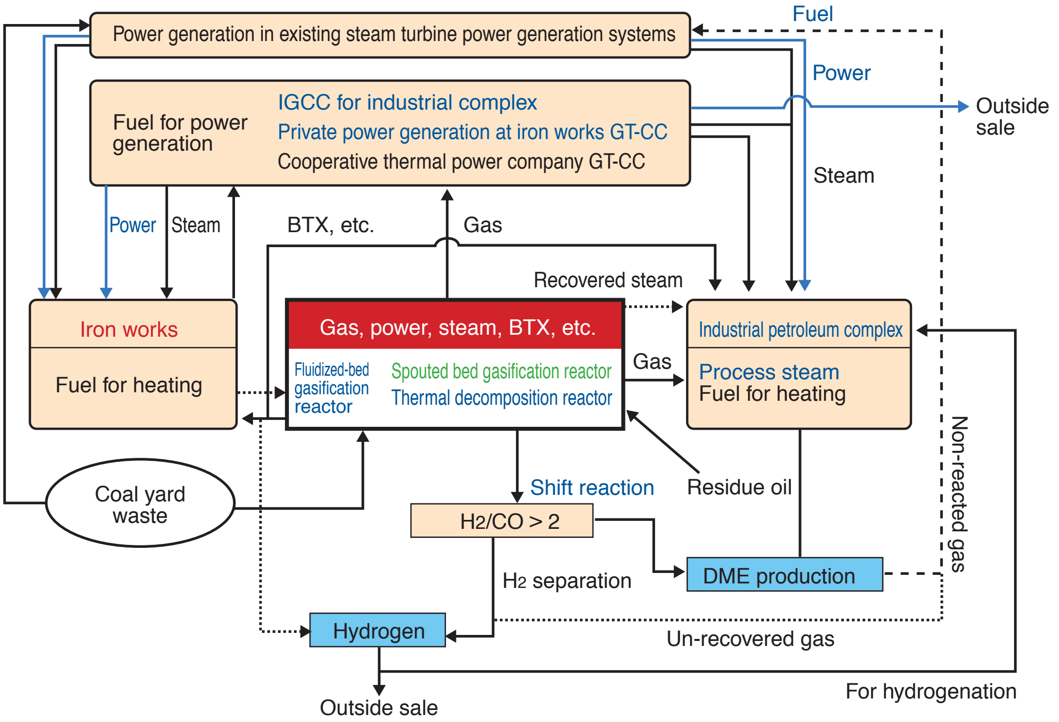


Fig. 2 Power generation, steam, fuel for process heating, hydrogen, and DME energy supply system in an iron works facility

Future Outlook for CCT

Looking ahead to the future of clean coal technology from the viewpoint of technical innovation in the coal industry, noted below are some very diverse technological trends that are crucial for society.

The first trend is that many different technologies or systems related to coal gasification are now under development. As an example, R&D on high-efficiency power generation systems, including the integrated coal gasification combined cycle (IGCC) and the integrated coal gasification fuel cell combined cycle (IGFC), has steadily progressed toward commercialization. Another example is conversion into liquid fuel or chemical raw materials that are clean and contain no impurities, such as methanol, DME and GTL. These technologies will lead to co-production systems, including co-generation, with a view to a zero-emission world.

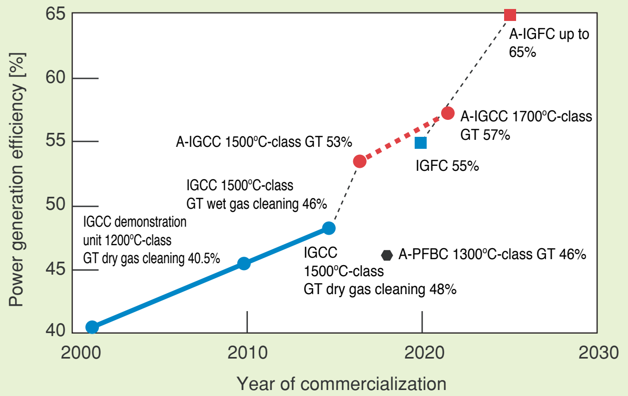


Fig. 1 Projection of improvement of generation efficiency

Source: The Institute of Applied Energy

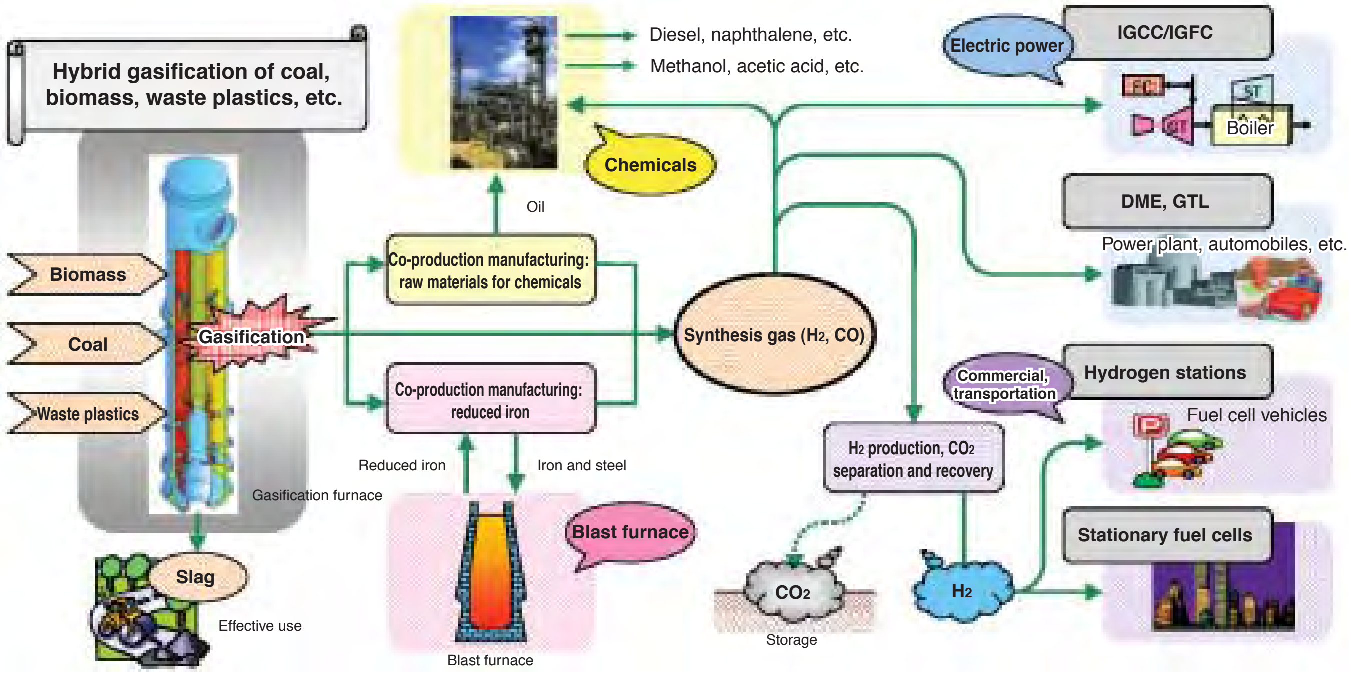


Fig. 2 Various CCT developments centering on coal gasification

The second trend is towards efforts to build a hydrogen energy society, which is the direction the energy sector is expected to move. According to the International Institute for Applied Systems Analysis 2000 (IIASA 2000), in terms of the "H/C (hydrogen/carbon)" ratio, global primary energy consumption was on a near-constant increase between the mid-1800's to around 1980. In and after 1980, the H/C ratio remained almost unchanged at around two due to an increase in oil consumption. As a whole, however, the pre-1980 trend is expected to resume, leading to a situation where, around 2030, the H/C ratio will equal four. In a society where the primary energy source is shifting from natural gas to hydrogen, energy consumption derived from carbon combustion will finally be discouraged. It is even predicted that coal energy will only be used for HyPr-RING (Hydrogen Production by

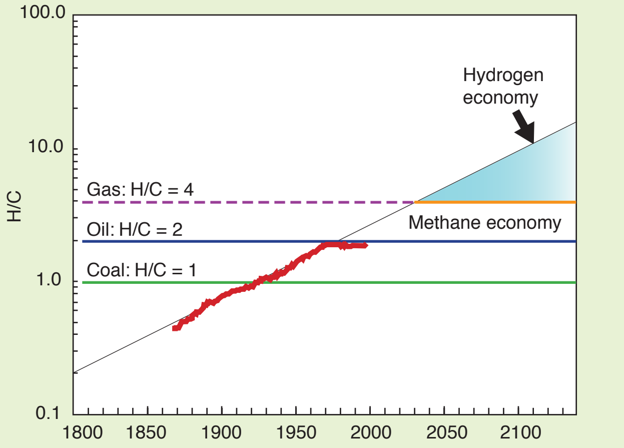


Fig. 3 Ratio of hydrogen to carbon (H/C) in primary energy

Prepared from IIASA 2000

Reaction Integrated Novel Gasification process, where the H/C ratio is approximately one), and society will be forced to deal with CO_2 emissions resulting from the direct combustion of coal by heavily relying on CO_2 separation, recovery, sequestration and fixation. Thus, there are basically two important clean coal technology challenges. One is to develop a series of upstream technologies to separate, recover, sequester and store CO_2 generated through the direct combustion of coal and to collect crude oil and gases. The other is to build high-efficiency coal utilization technologies, including coal gasification, reforming and conversion technologies, so that the carbon component in coal can be used as fuel or as a feedstock for the chemical industry, thereby reducing CO_2 emissions generated through direct combustion.

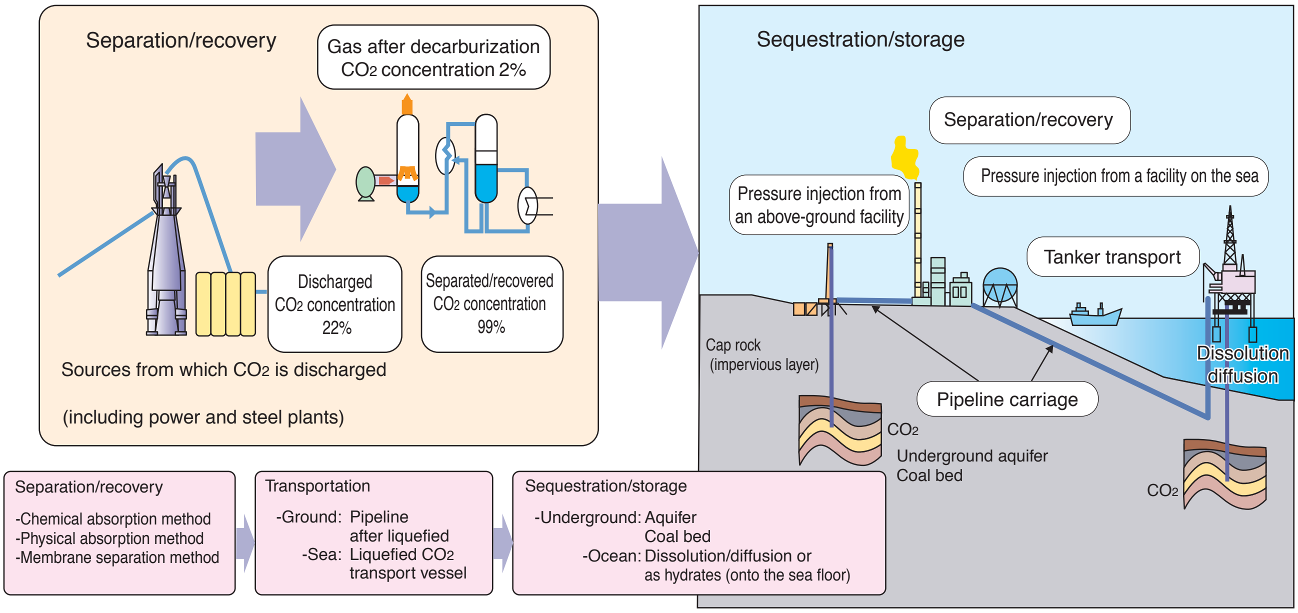


Fig. 4 CO_2 separation, recovery, sequestration, and storage

The third trend is exploiting coal technology's potential for technical development in association with innovative technologies such as environmental/energy technology, biotechnology, nanotechnology and information technology, which have been categorized as priority R&D target technologies in Japan.

Research and development of environmental/energy technology is focused on achieving a zero-emission society, mainly through the implementation of "CO_2 control," as mentioned earlier. The co-production system is regarded as the final target to be achieved through technical innovation.

Advances in biotechnology could also unlock methods for the fixation and effective utilization of CO_2. Furthermore, the development of hyper-coal production technology may bring about novel techniques that allow advanced utilization of the carbon within coal. In fact, there exist some specific nanotechnology areas, such as nanocarbon fibers, where potential technical innovation is associated with coal.

The progress in information technology will certainly bring about innovative developments in the modeling and simulation of coal technologies.

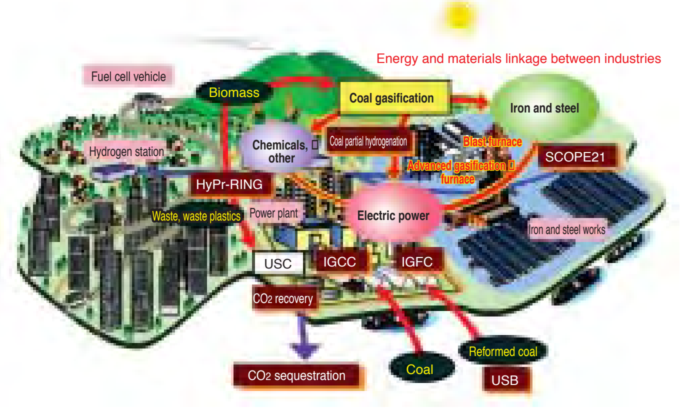


Fig. 5 Energy utilization in a future society supported by CCT (2030)

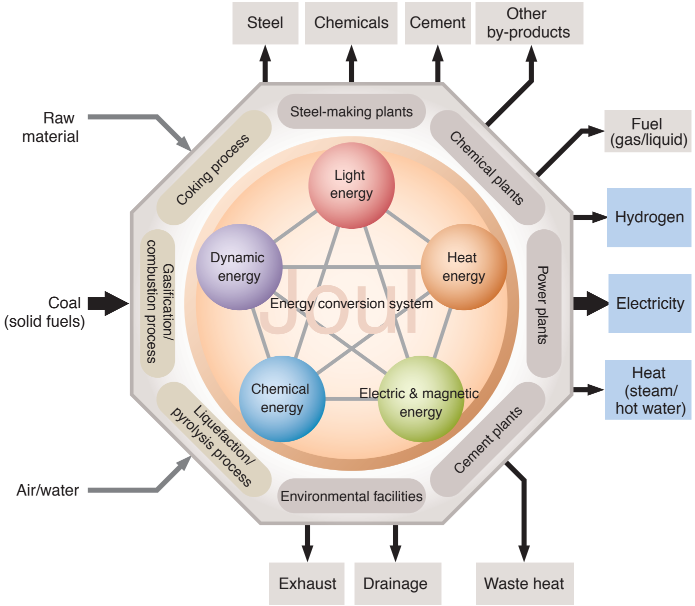


Fig. 6 Co-production system

The ultimate goal for co-production systems is zero emissions (or the discharge of purified water and steam).

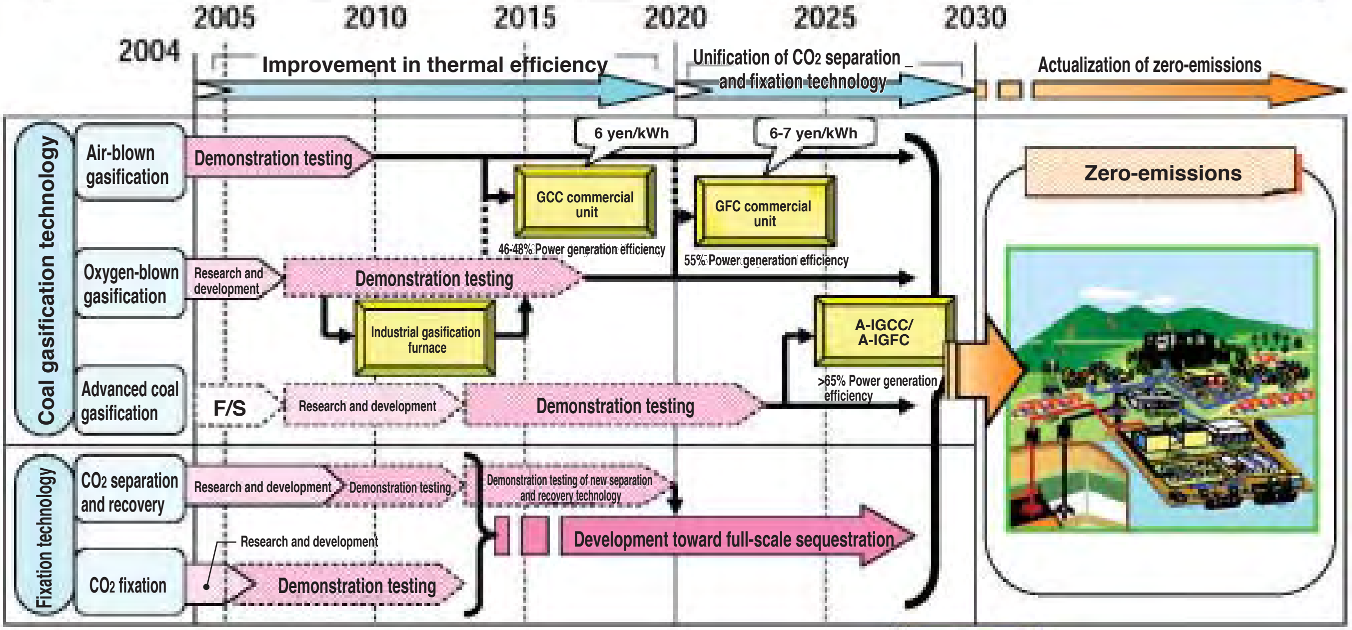
CCT plays an important role in steelmaking as well as in power generation. Coal is used in the steelmaking industry not only as an energy resource but also as a high-quality reducing agent, and is one of the raw materials used in steelmaking. A potential task to be assigned to well-established steelmaking processes, such as the blast-furnace process, is to achieve an innovative level of total coal utilization efficiency by using a co-production system, like DIOS (Direct Iron Ore Smelting reduction process), in order to simultaneously produce iron and synthetic gas, electric power, hydrogen/thermal energy, chemical feedstocks, etc., from steam coal for the steady implementation of improved environmental measures aimed at zero emissions.

As the world's largest coal importer and as the leader in CCT, Japan should remain active in international cooperation, including technical transfers and human resource development with developing countries, mainly in Asia. Such international activities will not only benefit countries that are trying to improve their economic growth by relying on coal energy, but also provide Japan itself with significant means to achieve a stable supply of energy. In addition, it will support efforts to utilize the Kyoto Mechanisms, including the Clean Development Mechanism (CDM), which seek to address global environmental problems.

Economic growth can only be achieved with a stable supply of energy, while environmental conservation is a challenge to be addressed by the whole world. The former is a limiting factor for the latter and vice versa. Throughout history, these two conflicting concerns have had the common fundamental problem of explosive population growth. Under these circumstances, efforts for environmental conservation, including controlling global warming with a goal of eliminating emissions, must be the top priority in the development of CCT in Japan. It is, therefore, essential to build an efficient, advanced coal energy utilization system with minimum impact on the global environment, which will require international cooperation.

Promotion of innovative CCT development toward eliminating emissions

With an aim to positioning coal as a source of CO_2-free energy by 2030, innovative CCT development will be promoted, including CO_2 fixation technology and next-generation high-efficiency gasification technology, toward the goal of eliminating emissions, while identifying the role of individual technologies in the overall scheme.



Current coal thermal generation unit price is assumed to be 5.9 yen/kWh, as estimated by The Federation of Electric Power Companies, Japan.

(1) Main SI units

Quantity	SI unit	Unit applicable with SI unit
Angle	rad	…(degree), ’(minute), ”(second)
Length	m	
Area	m^2	
Volume	m^3	ℓ (liter)
Time	s (Second)	d (day), h (hour), min (minute)
Frequency, vibration	Hz (Hertz)	
Mass	kg	t(ton)
Density	kg/m^2	
Force	N (Newton)	
Pressure	Pa (Pascal)	bar (bar)
Work, energy	J (Joule)	eV (electron voltage)
Power	W (Watt)	
Thermodynamic temperature	K (Kelvin)	
Quantity of heat	J (Joule)	

(2) Prefix of SI system

Multiple to the unit	Prefix	
	Name	Symbol
10^{18}	Exa	E
10^{15}	Peta	P
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	u
10^{-9}	nano	n
10^{-12}	pico	p

(3) Typical conversion factors

1. Basic Energy Units
   - 1J (joule)=0.2388cal
   - 1cal (calorie)=4.1868J
   - 1Bti (British)=1.055kJ=0.252kcal
2. Standard Energy Units
   - 1toe (tonne of oil equivalent)=42GJ=10,034Mcal
   - 1tce (tonne of coal equivalent)=7000Mcal=29.3GJ
   - 1 barrel=42 US gallons≒159 ℓ
   - $1m^3$=35,315 cubic feet=6,2898 barrels
   - 1kWh=3.6MJ≒860kcal
   - 1,000scm (standard cubic meters) of natural gas=36GJ (Net Heat Value)
   - 1 tonne of uranium=10,000-16,000toe(Light water reactor, open cycle)
   - 1 tonne of peat=0.2275toe
   - 1 tonne of fuelwood=0.3215toe

(4) Coal gasification reactions

Coal Pyrolysis

$$\text{Coal} \rightarrow CH_4 + C(\text{char/coke}) + (\text{Generated heat}) \quad (1)$$

Chemical reaction with oxygen

$$C + O_2 \rightarrow CO_2 + 97.0\text{kcal/mol} \quad (2)$$

$$C + \frac{1}{2}O_2 \rightarrow CO + 29.4\text{kcal/mol} \quad (3)$$

Chemical reaction with carbon dioxide

$$C + CO_2 \rightarrow 2CO - 38.2\text{kcal/mol} \quad (4)$$

Chemical reaction with steam

$$C + H_2O \rightarrow CO + H_2 - 31.4\text{kcal/mol} \quad (5)$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 - 18.2\text{kcal/mol} \quad (6)$$

$$CO + H_2O \rightarrow CO_2 + H_2 + 10.0\text{kcal/mol} \quad (7)$$

Chemical reaction with hydrogen

$$C + 2H_2 \rightarrow CH_4 + 17.9\text{kcal/mol} \quad (8)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O + 49.3\text{kcal/mol} \quad (9)$$

(5) Standard heating value for each energy source

Energy source	Unit	Standard calorific value	Standard calorific value on a Kcal basis	Former standard calorific value	Remarks
Coal					
Coal					
Imported coking coal	kg	28.9 MJ	6904 kcal	7600 kcal	Temporary value
Coking coal for coke	kg	29.1 MJ	6952 kcal	—	
Coking coal for PCI	kg	28.2 MJ	6737 kcal	—	
Imported steam coal	kg	26.6 MJ	6354 kcal	6200 kcal	
Domestic steam coal	kg	22.5 MJ	5375 kcal	5800 kcal	
Imported anthracite	kg	27.2 MJ	6498 kcal	6500 kcal	
Coal product					
Coke	kg	30.1 MJ	7191 kcal	7200 kcal	
Coke oven gas	Nm^3	21.1 MJ	5041 kcal	4800 kcal	
Blast furnace gas	Nm^3	3.41 MJ	815 kcal	800 kcal	
Converter gas	Nm^3	8.41 MJ	2009 kcal	2000 kcal	
Oil					
Crude oil					
Crude oil	ℓ	38.2 MJ	9126 kcal	9250 kcal	
NGL, Condensate	ℓ	35.3 MJ	8433 kcal	8100 kcal	Formerly NGL
Oil product					
LPG	kg	50.2 MJ	11992 kcal	12000 kcal	
Naphtha	ℓ	34.1 MJ	8146 kcal	8000 kcal	
Gasoline	ℓ	34.6 MJ	8266 kcal	8400 kcal	
Jet fuel	ℓ	36.7 MJ	8767 kcal	8700 kcal	
Kerosene	ℓ	36.7 MJ	8767 kcal	8900 kcal	
Gas oil	ℓ	38.2 MJ	9126 kcal	9200 kcal	
A-heavy oil	ℓ	39.1 MJ	9341 kcal	9300 kcal	
C-heavy oil	ℓ	41.7 MJ	9962 kcal	9800 kcal	
Lubrication oil	ℓ	40.2 MJ	9603 kcal	9600 kcal	
Other heavy oil product	kg	42.3 MJ	10105 kcal	10100 kcal	Formerly other oil products
Oil coke	kg	35.6 MJ	8504 kcal	8500 kcal	
Refinery gas	Nm^3	44.9 MJ	10726 kcal	9400 kcal	
Gas					
Flammable natural gas					
Imported natural gas (LNG)	kg	54.5 MJ	13019 kcal	13000 kcal	Formerly LNG
Domestic natural gas	Nm^3	40.9 MJ	9771 kcal	9800 kcal	Formerly natural gas
City gas					
City gas	Nm^3	41.1 MJ	9818 kcal	10000 kcal	
Electric power					
Generation side					
Heat supplied to power generator	kWh	9.00 MJ	2150 kcal	2250 kcal	Efficiency 39.98%
Consumption side					
Heat produced from electric power	kWh	3.60 MJ	860 kcal	860 kcal	
Heat					
Consumption side					
Heat produced from steam	kg	2.68 MJ	641 kcal	—	100°C, 1 atm Saturated steam

Clean Coal Technologies in Japan
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